UNITED STATES PATENT AND TRADEMARK OFFICE

BEFORE THE PATENT TRIAL AND APPEAL BOARD

GEOTAB INC. AND GEOTAB USA, INC.,
Petitioners,

v.

FRACTUS, S.A.
Patent Owner.

Case No. PGR2025-00056
Patent No. 12,095,149

DECLARATION OF JAMES L. MULLINS, Ph.D.

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I, James L. Mullins, declare as follows:

1. My name is James L. Mullins.

2. I have been retained by petitioners Geotab Inc. and Geotab USA, Inc. ("Petitioners") in the above-captioned post-grant review to provide opinions on various documents.

I. INTRODUCTION

3. I am presently Dean Emeritus of Libraries and Esther Ellis Norton Professor Emeritus at Purdue University. My career as a professional and academic/research librarian spanned more than 44 years, including library positions at Indiana University, Villanova University, Massachusetts Institute of Technology, and Purdue University. EX1015 is a true and correct copy of my curriculum vitae describing my background and experience.

4. In January 2018, I founded the firm Prior Art Documentation Librarian Services, LLC, located at 205 St. Cuthbert, Williamsburg, VA 23188 after purchasing the intellectual property of Prior Art Documentation, LLC located at 711 South Race Street, Urbana, IL 61801. Further information about my firm, Prior Art Documentation Librarian Services, LLC (PADLS), is available at https://www.priorartdoclib.com (last checked April 25, 2025).

5. I have been retained by Geotab Inc. and Geotab USA, Inc. to offer my opinion on the authenticity and dates of public accessibility of various documents. For this service, I am being paid my usual hourly fee of $275.00/hour. I have no stake in the outcome of this proceeding or any related litigation or administrative proceedings, and my compensation in no way depends on the substance of my testimony or the outcome of any proceeding.

II. QUALIFICATIONS

6. I received a Bachelor of Arts degree in History, Religion and Political Science in 1972 as well as a Master of Arts degree in Library Science in 1973 from the University of Iowa. I received my Ph.D. in Academic Library Management in 1984 from Indiana University. Over the past fifty years, I have held various positions in the field of library and information sciences.

7. I am presently Dean Emeritus of Libraries and Esther Ellis Norton Professor Emeritus at Purdue University, and have been since January 1, 2018. I have been previously employed as follows:

> Dean of Libraries and Professor and Esther Ellis Norton Professor, Purdue University, West Lafayette, IN (2004-December 31, 2017)
>
> Assistant/Associate Director for Administration, Massachusetts Institute of Technology (MIT) Libraries, Cambridge, MA (2000-2004)
>
> University Librarian and Director, Falvey Memorial Library, Villanova University, Villanova, PA (1996-2000)

Director of Library Services, Indiana University South Bend, South Bend, IN (1978-1996)

Part-time Instructor, School of Library and Information Science, Indiana University, Bloomington, IN (1979-1996)

Associate Law Librarian, and associated titles, Indiana University School of Law, Bloomington, IN (1974-1978)

Catalog Librarian, Assistant Professor, Georgia Southern College (now University), Statesboro, GA (1973-1974)

8. I have been a member of the American Library Association ("ALA") since 1974. I served as the chair of the Research Committee of the Association of College and Research Libraries ("ACRL"). My service included the editorial board of the most prominent library journal, *College and Research Libraries*. I also served on the Standards Committee, College Section of the Association of College and Research Libraries, where I was instrumental in developing a re-issue of the *Standards for College Libraries* in 2000.

9. For over 20 years I was actively engaged in academic library professional associations on the international level including invited papers and lectures in Germany, Norway, Israel, Argentina, Australia, South Africa, New Zealand, Hong Kong, Israel, Turkey, Greece, Canada, France, Belgium, China, Japan, South Korea, Finland, Sweden, Poland, Portugal, Spain, Switzerland, Singapore, and the United Kingdom.

10. I am an author of numerous publications in the field of library science, and have given presentations in library sciences at national and international conferences. During more than 44 years as an academic librarian and library science scholar, I have gained extensive experience with catalog records and online library management systems ("LMS") built using Machine-Readable Cataloging ("MARC") standards. As a part-time instructor at the School of Library and Information Science, Indiana University, I taught, as well as other courses, the cataloging course, "Organization of Library Materials."

11. As an academic library administrator, I have had responsibility to ensure that students were educated to identify, locate, assess, and integrate information garnered from research library resources. I have also facilitated the research of faculty colleagues either directly or through the provision of and access to the requisite print and/or digital materials and services at the universities where I worked.

12. Based on my experience identified above and detailed in my curriculum vitae (EX1015), I consider myself to be an expert in the field of library science and academic library administration. I have previously offered my opinions on the public availability and authenticity of documents in over 150 cases.

III. BACKGROUND ON PUBLIC ACCESSIBILITY

A. Scope of This Declaration

13. I am not a lawyer, and I am not rendering an opinion on the legal question of whether a particular document is, or is not, a "printed publication" under the law. I am, however, rendering my expert opinion on the authenticity of particular documents referenced herein and when and how these documents were disseminated or otherwise made available to the extent that people interested and ordinarily skilled in the subject matter or art, exercising reasonable diligence, could have located the documents.

14. I am informed by counsel for Petitioners that a document is considered authentic if there is sufficient evidence to support a finding that the item is what it is claimed to be. I am also informed by counsel for Petitioners that authenticity can be established based on the contents of the document itself, such as the appearance, content, substance, internal patterns, or other distinctive characteristics of the document.

15. I am informed by counsel for Petitioners that a given reference qualifies as "publicly accessible" if it was disseminated or otherwise made available such that a person interested in and ordinarily skilled in the relevant subject matter or art could locate it through the exercise of reasonable diligence.

16. While I understand that the determination of public accessibility under the foregoing standard rests on a case-by-case analysis of the facts particular to an individual publication, I am also informed by counsel for Petitioners that a document is considered "publicly accessible" if it is cataloged and indexed by a library such that a person interested in the relevant subject matter could locate it through the exercise of reasonable diligence (*i.e.*, I understand that cataloging and indexing by a library is sufficient, though there are other ways that a document may qualify as "publicly accessible"). One manner of sufficient indexing is indexing according to subject matter. I understand that it is not necessary to prove someone actually looked at the document in order to show it was publicly accessible by virtue of a library's cataloging and indexing thereof. I understand that cataloging and indexing by a single library of a single instance of a particular document is sufficient for public accessibility.

17. I understand that evidence showing the specific date when a reference became publicly accessible is not necessary. Rather, routine business practices, such as general library cataloging and indexing practices, can be used to establish a date by which a reference became publicly accessible.

B. Person of Ordinary Skill in the Art

18. In forming the opinions expressed in this declaration, I have reviewed the documents and appendices referenced herein. These materials are records created in the ordinary course of business by publishers, libraries, indexing services, and/or others. From my years of experience, I am familiar with the process for creating many of these records, and I know that these records are created by people with knowledge of the information contained within the record.

19. Further, these records are created with the expectation that researchers and other members of the public will use them. All materials cited in this declaration and its exhibits are of a type that experts in my field would reasonably rely upon and refer to in forming their opinions.

20. Counsel for Petitioners informed me that the subject matter of this proceeding relates to mobile communication devices including antennas for receiving or transmitting electromagnetic wave signals.

21. I have been informed by Petitioners' counsel that a "person of ordinary skill in the art at the time of the invention" (POSA) is a hypothetical person who is presumed to be familiar with the relevant field and its literature at the time of the invention. This hypothetical person is also a person of ordinary creativity, capable of understanding the scientific and/or engineering principles applicable to the pertinent field.

22. Petitioners' counsel has informed me that a POSA in this subject matter or art would have had at least a bachelor's degree in electrical engineering, computer science, or a similar degree and at least four years of experience in applied electromagnetics with an emphasis on antennas. Alternatively, a POSA would have a master's degree in electrical engineering (or similar discipline) and at least two years of similar experience.

C. Library Catalog Records and Other Resources

23. Some background on MARC (Machine-Readable Cataloging) formatted records, OCLC (addressed below), and *WorldCat* (addressed below) is helpful to understand the library catalog records discussed in this declaration. I am fully familiar with the library cataloging standard known as the MARC standard, which is an industry-wide standard method of storing and organizing library catalog information.[1] MARC practices have been consistent since the MARC format was developed by the Library of Congress in the 1960s, and by the early 1970s MARC became the U.S. national standard for disseminating bibliographic data. By the mid-1970s, MARC format became the international standard, and it persists through the present. A MARC-compatible library is one that has a catalog

[1] The full text of the standard is available from the Library of Congress at http://www.loc.gov/marc/bibliographic/ (last checked April 25, 2025).

consisting of individual MARC records for each of its items. The underlying MARC format (computer program) underpins the online public access catalog ("OPAC") available to library users to locate a particular holding of a library. Today, MARC is the primary communications protocol for the transfer and storage of bibliographic metadata in libraries.[2] The MARC practices discussed below were in place during the time frame relevant to the documents discussed herein.

24. Online Computer Library Center ("OCLC") is a not-for-profit worldwide consortium of libraries. Similar to MARC standards, OCLC's practices have been consistent from the 1970s through the present. Accordingly, the OCLC practices discussed below were in place during the time frame discussed in my

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[2] Almost every major library in the world uses a catalog that is MARC-compatible. *See, e.g.*, Library of Congress, *MARC Frequently Asked Questions (FAQ)*, https://www.loc.gov/marc/faq.html (last visited April 25, 2025) ("MARC is the acronym for MAchine-Readable Cataloging. It defines a data format that emerged from a Library of Congress-led initiative that began nearly forty years ago. It provides the mechanism by which computers exchange, use, and interpret bibliographic information, and its data elements make up the foundation of most library catalogs used today."). MARC is the ANSI/NISO Z39.2-1994 (reaffirmed 2009) standard for Information Interchange Format.

opinions section (§IV). OCLC was created “to establish, maintain and operate a computerized library network and to promote the evolution of library use, of libraries themselves, and of librarianship, and to provide processes and products for the benefit of library users and libraries, including such objectives as increasing availability of library resources to individual library patrons and reducing the rate of rise of library per-unit costs, all for the fundamental public purpose of furthering ease of access to and use of the ever-expanding body of worldwide scientific, literary and educational knowledge and information.”[3] Among other services, OCLC and its members are responsible for maintaining the *WorldCat* database (http://www.worldcat.org/), used by libraries throughout the world.

25. *WorldCat* is the world’s largest public online catalog, maintained by the OCLC, a not-for-profit international library consortium, built with the records created by the thousands of libraries that are members of OCLC.

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[3] OCLC Online Computer Library Center, Inc., *Amended Articles of Incorporation of OCLC Online Computer Library Center, Inc.*, Third Article (OCLC, Dublin, Ohio) Revised November 30, 2016, https://www.oclc.org/content/dam/oclc/membership/articles-oA-incorporation.pdf (last checked April 25, 2025).

D. Periodical/Serial Publications

26. A periodical publication is a published work in a series, for example, a journal article. A library typically creates a catalog record for a periodical publication when the library receives its first issue. When the library receives subsequent issues or volumes of the periodical, the issues or volumes are checked in, often using a date stamp, added to the library's holding records, and made available and searchable very soon thereafter, normally within a few days of receipt. This practice continued up to the time when many scholarly journals ended printing a paper edition, and only published in digital format, depending upon the journal between 2005–2014.

E. Cataloging / Indexing

27. A researcher may discover material relevant to a topic of interest in a variety of ways. One common means of discovery is to search for relevant information in an index of periodicals and other publications. Having found relevant material, the researcher will then normally obtain it online, look for it in libraries, or purchase it from a publisher, a bookstore, a document delivery service, or another provider.

28. Indexing services use a wide variety of controlled vocabularies to provide subject access and other means of discovering the content of documents. The formats in which these access terms are presented vary from service to service.

29. Online indexing services commonly provide bibliographic information, abstracts, and full-text copies of the indexed publications, along with a list of the documents cited in the indexed publication. These services also often provide lists of publications that cite a given document.

F. Databases and Libraries Consulted

30. ***IEEE Xplore*** – The Institute of Electrical and Electronics Engineers is the world's largest organization for the advancement of technology with some 430,000 members in 160 countries. Known by its acronym IEEE, it has created a database, IEEE Xplore, that provides access to its hundreds of publications and those of it publishing partners. This include the content of over 170 journals, more than 1,400 conference proceedings, some 5,100 technical standards, 2,000 eBooks and 400 educational courses. In all, more than 3 million documents, dating from 1872 on, are searchable and available for purchase either through subscription or individually. Many of these records are accessible via Google Scholar. https://ieeexplore.ieee.org/Xplore/home.jsp

31. ***IET Digital Library*** **–** The IET Digital Library showcases the science, engineering, and technology focused content produced by one of the world's largest engineering institutions with more than 156,000 engineering and technology professionals in 148 countries. Bringing together 48 current journals, our journal archive, 900 eBooks, E+T natural home for academia, practitioners

and industry. IET Digital Library is database created and maintained by the Institution of Engineering and Technology located in the United Kingdom. https://digital-library.theiet.org/

32. ***Linda Hall Library*** – "The Linda Hall Library is a privately-endowed American library of science, engineering and technology located in Kansas City, Missouri … Established in 1946 through the philanthropy of Linda and Herbert F. Hall … the library is open to the public, and invites individual researchers, academic institutions, and companies from Kansas City and around the world to use the library's research-level collection. Its mission is to act as 'guardian of the collective intellectual heritage with regard to the science, technology, and engineering disciplines.'" https://en.wikipedia.org/wiki/Linda_Hall_Library (last checked April 25, 2025).

IV. OPINION REGARDING AUTHENTICITY AND PUBLIC ACCESSIBILITY

A. EX1009: P. Ciais, R. Staraj, G. Kossiavas, and C. Luxey. "Design of an Internal Quad-Band Antenna for Mobile Phones," *IEEE Microwave and Wireless Components Letters*, vol. 14, no. 4, pp. 148-150, April 2004 ("Ciais-Quadband").

33. I have been asked to opine on an article, authored by P. Ciais, R. Staraj, G. Kossiavas, and C. Luxey, titled "Design of an Internal Quad-Band Antenna for Mobile Phones," published in *IEEE Microwave and Wireless Components Letters*, vol. 14, no. 4, pp. 148-150, April 2004 ("Ciais-Quadband").

34. Within this declaration Ciais-Quadband will indicate both the article titled "Design of an Internal Quad-Band Antenna for Mobile Phones," as well as the issue of *IEEE Microwave and Wireless Components Letters,* vol. 14, no. 4*,* April 2004, dependent upon context.

1. Authentication

35. I have evaluated the Ciais-Quadband reference three ways: (1) by assessing the copy of Ciais-Quadband (EX1009), provided to me by Petitioners' counsel and obtained by them from digital copy available for a fee from *IEEE Xplore*; (2) by assessing scans of a print copy of Ciais-Quadband owned by the Linda Hall Library, provided to me by the Linda Hall Library Document Delivery Service, Attachment A-1; and (3) by accessing and reviewing Ciais-Quadband in digital format available to me as an emeritus faculty member through Purdue University Libraries, Attachment A-2.

36. EX1009 (Ciais-Quadband), has been provided to me by petitioners' counsel. I see no evidence that any alteration, deletion or addition of pages, etc., were made to EX1009.

37. Attachment A-1 was provided to me at my request on May 5, 2025, by Linda Hall Library Document Services from the copy owned by the Linda Hall Library. Attachment A-1 includes scans of Ciais-Quadband: cover of issue April 2004, volume 14, number 4, April 2004, ISSN 1531-1305, with a stamp that reads,

"Linda Hall May 07 2004 Library", as shown below; the Ciais-Quadband article, pages 148-150.

38. All identifying characteristics, such as stamps and notations on Attachment A-1, are consistent with library practice and procedure that I have observed during my career as a professional librarian. I have no cause for doubt about the authenticity or accuracy of these identifying attributes.

39. Attachment A-1 was found within the custody of a library, the Linda Hall Library, one of the most likely locations for an authentic document to be publicly accessible. Evidence of the ownership of Ciais-Quadband by the Linda Hall Library will further be explored and detailed in the section below on public access (§IV.A.2).

40. Attachment A-2 is a download of Ciais-Quadband that I made on May 6, 2025, from the *IEEE Xplore* database as an emeritus faculty member at Purdue University at this URL:

https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=1291446

Ciais-Quadband is available from *IEEE Xplore* for a fee at this URL:

https://ieeexplore.ieee.org/document/1291446

41. After my comparison between EX1009 (Ciais-Quadband), and Attachment A-1, and Attachment A-2, I found no difference between EX1009 (Ciais-Quadband), and Attachment A-1 and Attachment A-2.

42. Therefore, I affirm, after verifying EX1009 against Attachment A-1, and Attachment A-2, that EX1009 is a complete and accurate version of Ciais-Quadband.

43. Therefore, with the evidence that Ciais-Quadband is held in the Linda Hall Library (Attachment A-1), and accessing and retrieving Ciais-Quadband from the *IEEE Xplore* database through the Purdue University Libraries (Attachment A-2), I have determined that EX1009 (Ciais-Quadband) is an authentic document.

44. I conclude and affirm that EX1009 (Ciais-Quadband) is an authentic document.

2. Public Accessibility

45. Attachment A-3 is a true and correct copy of the *WorldCat* entry for *IEEE Microwave and Wireless Components Letters.* I obtained Attachment A-3 by completing a search on *WorldCat* on May 7, 2025 by searching for libraries holding this journal near Kansas City, Missouri.

46. Attachment A-3 shows that *IEEE Microwave and Wireless Components Letters* is the journal associated with this *WorldCat* entry, as verified

by title: *IEEE Microwave and Wireless Components Letters;* publisher: Institute of Electrical and Electronics Engineers (IEEE); and ISSN: 1531-1309.

47. *IEEE Microwave and Wireless Components* could have been located in *WorldCat* by searching for the title of the journal: *IEEE Microwave and Wireless Components Letters*; and/or by searching the subject headings: "*Microwave communications systems;* and/or "*Microwave devices*," among others.

48. When I searched *WorldCat* for holdings of *IEEE Microwave and Wireless Components Letters* near Kansas City, Missouri, the Linda Hall Library was second on the list among the 698 libraries shown as holding *IEEE Microwave and Wireless Components Letters* near Kansas City, Missouri.

49. Attachment A-4 is a download I made from the Linda Hall Library OPAC on May 7, 2025. The journal catalogued in this record is *IEEE Microwave and Wireless Components Letters,* as verified by the OPAC record fields including title: *IEEE Microwave and Wireless Components Letters*; publisher: Institute of Electrical and Electronics Engineers (IEEE); and ISSN: 1531-1309.

50. The record of holdings of *IEEE Microwave and Wireless Components Letters* by the Linda Hall Library is shown in the line titled: "Holdings:" that reads: "Vol.14 no.1 (January 2004) – Vol.14 no. 5, as shown below, indicates that *IEEE Microwave and Wireless Components Letters* was received and is presently held by the Linda Hall Library.

Linda Hall Library

Available , Closed Stacks - Serials ; IEEE microwave & wireless components letters.

Holdings:

Vol. 11 no. 1 (January 2001) -Vol. 12 no. 12 (December 2002)
Vol. 13 no. 1 (January 2003) -Vol. 13 no. 3 (March 2003)
Vol. 13 no. 4 (April 2003)
Vol. 13 no. 5 (May 2003) -Vol. 13 no. 12 (December 2003)
Vol. 14 no. 1 (January 2004) -Vol. 14 no. 5 (May 2004)
Vol. 14 no. 7 (July 2004) -Vol. 16 no. 12 (December 2006)
Vol. 17 no. 1 (January 2007) -Vol. 17 no. 10 (October 2007)
Vol. 17 no. 12 (December 2007)
Vol. 18 no. 1 (January 2008) -Vol. 18 no. 3 (March 2008)
Vol. 18 no. 6 (June 2008) -Vol. 18 no. 12 (December 2008)
Vol. 19 no. 1 (January 2009) -Vol. 19 no. 12 (December 2009)

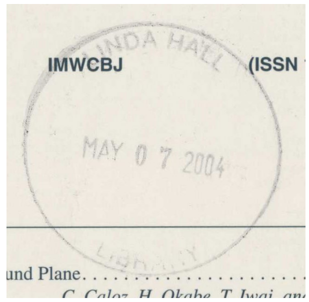
View less

Vol. 14 no. 1 (January 2004) -Vol. 14 no. 5 (May 2004)

51. *IEEE Microwave and Wireless Components Letters*, vol. 14, no. 4 April 2004, EX 1009, Ciais-Quadband, could have been located in the Linda Hall Library OPAC by searching for the title: “*IEEE Microwave and Wireless Components Letters*.

52. Although the nominal publication date of *IEEE Microwave and Wireless Components Letters,* volume 14, number 4, is April 2004, from my experience and knowledge it would not be inconsistent for a journal to be published, distributed to subscribers and libraries, and received and shelved in libraries prior to or after the nominal publication date.

53. For example, in this case, while the front cover of Ciais-Quadband (EX1009) indicates that the nominal publication date is April 2004, it was not checked in at the Linda Hall Library until May 7, 2004, as shown below.



54. After a date stamp is applied to a holding, it is promptly sent for shelving. The amount of time it takes to be shelved (available to the public) varies depending on the nature of the item, monograph, or journal issue. Monographs typically take longer than journals because cataloguing of monographs is more work-intensive. Journals, such as *IEEE Microwave and Wireless Components Letters*, Ciais-Quadband, are, more likely than not, entered into the general collection, shelved, and publicly accessible within two to five days of application of a date stamp by a library.

55. Therefore, the print copy of Ciais-Quadband (EX1009) at the Linda Hall Library would have been available for public access, more likely than not, by May 12, 2004.

56. Once Ciais-Quadband (EX1009) was entered into the general collection of the Linda Hall Library, researchers could access Ciais-Quadband by having it taken to the public reading room.

3. Conclusion

57. Ciais-Quadband (EX1009) is an authentic document and would have been publicly accessible, more likely than not, in the Linda Hall Library by May 12, 2004. Ciais-Quadband also would have been received by subscribers, more likely than not, by May 7, 2004, just as it was received in the Linda Hall Library no later than, and likely earlier than, May 7, 2004.

B. EX1010: P. Ciais, R. Staraj, G. Kossiavas, and C. Luxey. "Compact Internal Multiband Antenna for Mobile Phone and WLAN Standards," *Electronics Letters*, vol. 40, no. 15, pp. 920-921 (July 22, 2004) ("Ciais-Multiband")

58. I have been asked to opine on an article, authored by P. Ciais, R. Staraj, G. Kossiavas, and C. Luxey. "Compact Internal Multiband Antenna for Mobile Phone and WLAN Standards," published in *Electronics Letters*, volume 40, number 15, pp. 920-921, July 22, 2004. ("Ciais-Multiband")

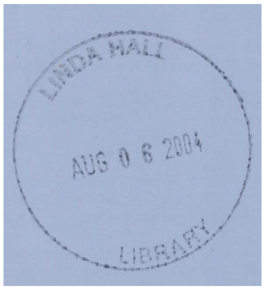
59. Within this declaration Ciais-Multiband will indicate both the article titled "Compact Internal Multiband Antenna for Mobile Phone and WLAN Standards," as well as the issue of *Electronics Letters*, volume 40, number 15, July 22, 2004, dependent upon context.

1. Authentication

60. I have evaluated the Ciais-Multiband reference three ways: (1) by assessing the copy of Ciais-Multiband (EX1010), provided to me by Petitioners' counsel and obtained by them from digital copy available for a fee from *IET Digital Library*; (2) by assessing scans of a print copy of Ciais-Multiband owned by the Linda Hall Library, provided to me by the Linda Hall Library Document Delivery Service, Attachment B-1; and (3) by accessing and reviewing Ciais-Multiband in digital format available to me as an emeritus faculty member through Purdue University Libraries, from *IET Digital Library*, Attachment B-2.

61. EX1010 (Ciais-Quadband), has been provided to me by petitioners' counsel. I see no evidence that any alteration, deletion or addition of pages, etc., were made to EX1010.

62. Attachment B-1 was provided to me at my request on May 5, 2025, by Linda Hall Library Doc Services from the copy owned by the Linda Hall Library. Attachment B-1 includes scans of Ciais-Quadband; cover of issue, *Electronics Letters*, volume 40, number 15, 22nd July 2004, ISSN 0013-5194, with a stamp that reads, "Linda Hall AUG 06 2004 Library", as shown below; and a bar code label, as shown below; contents pages [two] with the same ownership and date stamp as shown below; and the Ciais-Multiband article, pages 920-921.



33690028357995
Linda Hall Library

63. All identifying characteristics, such as stamps and notations on Attachment B-1, are consistent with library practice and procedure that I have observed during my career as a professional librarian. I have no cause for doubt about the authenticity or accuracy of these identifying attributes.

64. Attachment B-1 was found within the custody of a library, the Linda Hall Library, one of the most likely locations for an authentic document to be publicly accessible. Evidence of the ownership of Ciais-Multiband by the Linda Hall Library will further be explored and detailed in the section below on public access (§IV.A.2).

65. Attachment B-2 is a download of Ciais-Multiband that I made on May 9, 2025, from the *IET Digital Library* as an emeritus faculty member at Purdue University at this URL: https://digital-library-theiet-org.ezproxy.lib.purdue.edu/doi/10.1049/el%3A20045026

Ciais-Multiband is available from *IET Digital Library* for a fee at this URL:

https://digital-library.theiet.org/doi/abs/10.1049/el%3A20045026

66. After my comparison between EX1010 (Ciais-Quadband) and Attachment B-1, and Attachment B-2, I found no difference between EX1010 (Ciais-Quadband), and Attachment B-1 and Attachment B-2.

67. Therefore, I affirm, after verifying EX1010 against Attachment B-1, and Attachment B-2, that EX1010 is a complete and accurate version of Ciais-Quadband.

68. Therefore, with the evidence that Ciais-Multiband is held in the Linda Hall Library (Attachment B-1), and accessing and retrieving Ciais-Multiband from the *IET Digital Library* database through the Purdue University Libraries (Attachment B-2), I have determined that EX1010 (Ciais-Quadband) is an authentic document.

69. I conclude and affirm that EX1010 (Ciais-Quadband) is an authentic document.

2. Public Accessibility

70. Attachment B-3 is a true and correct copy of the WorldCat entry for. *Electronic Letters* that I obtained by completing a search on WorldCat on May 8, 2025 by searching for libraries holding this journal near Kansas City, Missouri, United States.

71. Attachment B-3 shows that *Electronic Letters* is the journal associated with this *WorldCat* entry, as verified by title*; Electronic Letters;* publisher: Institution of Elec; and ISSN: 0015-5194.

72. *Electronic Letters* could have been located in *WorldCat* by searching for the title of the journal: "*Electronic Letters;"* and/or by searching the subject headings: "*Electrical and Electronic Engineering;* and/or "*Electronics*," among others.

73. When I searched *WorldCat* for holdings of *Electronic Letters* near Kansas City, Missouri, the Linda Hall Library was third on the list among the 1,741 libraries shown as holding *Electronic Letters* near Kansas City, Missouri, United States.

74. Attachment B-4 is a download I made from the Linda Hall Library OPAC (online catalog) on May 8, 2025. The journal catalogued in this record is *Electronic Letters* as verified by the OPAC record fields including title: *Electronic Letters*; publisher: Institution of Engineering and Technology: and ISSN: 0013-5194.

75. Evidence that the Linda Hall Library received and holds Ciais-Multiband is shown in the OPAC record, Attachment B-4, in the area with the heading "Location - Holdings", that reads: *"v.36(2000) – v.46(2010)* as shown below, this is inclusive of volume 40, number 15, July 22, 2004.

LOCATION ITEMS

Linda Hall Library

Available , Closed Stacks - Serials ; Electronics letters.

Holdings:

v.1(1965)-v.34(1998); v.35(1999)

v.36(2000)-v.46(2010)

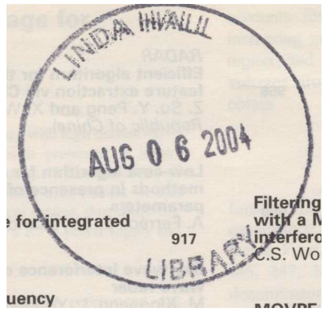
v.47:no.1(2011:Jan.6)-v.47:no.10(2011:May 12),v.47:no.13(2011:Jun.23)-v.49:no.25(2013:Dec.5)-

v.36(2000)-v.46(2010)

76. *Electronics Letters* could have been located in the Linda Hall Library OPAC by searching for the title: "*Electronic Letters.*

77. Although the nominal publication date of *Electronic Letters*, volume 40, number 15, July 22, 2004, from my experience and knowledge it would not be inconsistent for a journal to be published, distributed to subscribers and libraries, and received and shelved in libraries prior to or after the nominal publication date.

78. For example, in this case, while the front cover of Ciais-Multiband (EX1010) indicates that the nominal publication date of , volume 40, number 15, is July 22, 2004, the date stamped on EX1010 – "Aug 06 2004," as shown below – indicates receipt of Ciais-Multiband by the Linda Hall Library on August 6, 2004, a delay for distribution could be the result of various factors, for instance: editing or printing delays.



79. After a date stamp is applied to a holding, it is promptly sent for shelving. The amount of time it takes to be shelved (available to the public) varies depending on the nature of the item, monograph, or journal issue. Monographs typically take longer than journals because cataloguing of monographs is more work-intensive. Journals, such as Ciais-Quadband, are more likely than not, entered into the general collection, shelved, and publicly accessible within two to five days of application of a date stamp by a library.

80. Therefore, the print copy of Ciais-Multiband (EX1010) at the Linda Hall Library would have been available for public access, more likely than not, by August 11, 2004.

81. Once Ciais-Multiband (EX1010) was entered into the general collection of the Linda Hall Library, members of the public could access Ciais-Quadband in the Reading Room.

82. As I mentioned above in this section, a publication is first received in the library's mailroom, and then is routed to an intake desk where it receives a date

stamp. Thus, Ciais-Multiband was received, more likely than not, in Linda Hall Library mailroom sometime before the stamp was applied on August 6, 2004.

83. The Linda Hall Library, more likely than not, received Ciais-Multiband sometime before the stamp was applied on August 6, 2004, therefore, individual subscribers to *Electronics Letters,* volume 40, number 15, July 22, 2004 would also have, more likely than not, received Ciais-Multiband before August 6, 2004.

84. The physical copy of Ciais-Multiband at the Linda Hall Library would have been available for public access in Linda Hall Library after it was "checked-in," stamped with the date of August 6, 2004, and sent for shelving, more likely than not, within two to five days. Therefore, Ciais-Multiband was, more likely than not, available for public access in the Linda Hall Library by August 11, 2004.

3. Conclusion

85. Ciais-Multiband (EX1010) is an authentic document and would have been publicly accessible, more likely than not, in the Linda Hall Library by August 11, 2004. Ciais-Multiband also would have been received by subscribers, more likely than not, by August 6, 2004, just as it was received in the Linda Hall Library no later than, and likely earlier than, August 6, 2004.

C. EX1011: X. Jing, Z. Du, and K. Gong. "Compact Planar Monopole Antenna for Multi-band Mobile Phones," in *2005 Asia-Pacific Microwave Conference Proceedings*, vol. 4, part 4, pages 2657-2660. IEEE, 2005 ("Jing").

86. I have been asked to opine on an article, authored by X. Jing, Z. Du, and K. Gong titled, "Compact Planar Monopole Antenna for Multi-band Mobile Phones," published in *2005 Asia-Pacific Microwave Conference Proceedings*, volume 4, IEEE, 2005. ("Jing")

87. Within this declaration Jing will indicate both the article titled "Compact Planar Monopole Antenna for Multi-band Mobile Phones," as well as the *2005 Asia-Pacific Microwave Conference Proceedings*, dependent upon context.

1. Authentication

88. I have evaluated the Jing reference three ways: (1) by assessing the copy of Jing (EX1011), provided to me by Petitioners' counsel and obtained by Petitioners' counsel from a print copy held by the Massachusetts Institute of Technology (MIT); (2) by retrieving and assessing from the *IEEE Xplore* database a record of the deposit and availability of Jing within the IEEE Xplore database, Attachment C-1; and (3) by accessing and reviewing Jing in digital format available to me as an emeritus faculty member through Purdue University Libraries, from *IEEE Xplore*, Attachment C-2.

89. EX1011, Jing, has been provided to me by petitioners' counsel. I see no evidence that any alteration, deletion or addition of pages, etc., were made to EX1011. EX1011 is comprised of scans of the print copy of Jing as published in the print form in the *2005 Asia-Pacific Microwave Conference Proceedings*, vol. 4, IEEE, 2005 and held in the Barker Library, MIT Libraries.

90. All stamps and labels on EX1011, Jing, are consistent with the procedure and process at the MIT Libraries that I observed during my tenure as a librarian at MIT Libraries.

91. In EX1011:

- the first image (page one of the pdf) is a scan of the spine of volume 4, of the *2005 Asia-Pacific Microwave Conference Proceedings*, with a call number label that reads, "TK7876.A75 2005 v.4";
- the second image (page two of the pdf) is the cover of volume 4 with a bar code indicating MIT Libraries;
- the third image (page three of the pdf) is the inside front cover with a stamp that reads "Massachusetts Institute of Technology Libraries";
- the fourth image (page four of the pdf) is the inside cover flyleaf page with a handwritten call number that reads, "TK7876.A75 2005 v.4" and a stamp that reads, "MIT LIBRARIES BARKER MAY 10 2006 RECEIVED";

- the fifth image (page five of the pdf) is the proceedings volume 4 title page;
- the sixth image (page six of the pdf, internal page number ii) is the verso of the title page (copyright page);
- the seventh image (page seven of the pdf, internal page number x) is one page of the contents of volume 4 listing Jing (P4.62 at p. 2657);
- the eighth through eleventh images (pages 2657 to 2660) are the Jing article, "Compact Planar Monopole Antenna for Multi-band Mobile Phones."

92. All labels, stamps, etc., mentioned above, have been inserted below.

93. All identifying characteristics on EX1011, Jing, are consistent with library practice and procedure that I have observed during my career as a professional librarian, and specifically as seen during my tenure as a librarian at MIT Libraries. I have no cause for doubt about the authenticity or accuracy of these identifying attributes.

94. EX1011 was found within the custody of a library, the MIT Libraries, one of the most likely locations for an authentic document to be publicly accessible.

95. Attachment C-1 is a download of Jing that I made on May 11, 2025, from the *IEEE Xplore* database as an emeritus faculty member at Purdue University at the URL:

https://purdue.primo.exlibrisgroup.com/discovery/fulldisplay?docid=cdi_IEEE_primary_1606884&context=PC&vid=01PURDUE_PUWL:PURDUE&lang=en&search_scope=MyInst_and_CI&adaptor=Primo%20Central&tab=Everything&query=any,contains,Compact%20Planar%20Monopole%20Antenna%20for%20Multi-band%20Mobile%20Phones

96. Jing is available from *IEEE Xplore* database for a fee at the URL: https://IEEExplore.IEEE.org/document/1606884

97. After my comparison between EX1011 and Attachment C-1, I found no difference between EX1011, Jing, and Attachment C-1.

98. Therefore, I affirm, after verifying EX1011, Jing, the scan from the MIT Libraries print copy, against Attachment C-1, downloaded through Purdue University Libraries from *IEEE Xplore*, that EX1011 is a complete and accurate version of EX1011, Jing.

99. Therefore, with the evidence that Jing is held in the MIT Libraries, in print, EX1011, and accessing and retrieving Jing from the *IEEE Xplore* database through the Purdue University Libraries (Attachment C-1), I have determined that EX1011 is an authentic document.

100. I conclude and affirm that EX1011 is an authentic document.

2. Public Accessibility

101. Attachment C-2 is a screen capture I created on May 11, 2025 from the *IEEE Xplore* database the URL noted in the header of Attachment C-2.

102. Attachment C-2 includes the following points:

Title:

Compact planar monopole antenna for multi-band mobile phones

Publisher: **Publisher: IEEE**

Authors:

Xu Jing ; Zhengwei Du ; Ke Gong **All Authors**

Published in: 2005 Asia-Pacific Microwave Conference Proceedings

Date of Conference: 04-07 December 2005

Date Added to IEEE *Xplore*: 20 March 2006

Print ISBN:0-7803-9433-X

ISSN Information:

Print ISSN: 2165-4727

Electronic ISSN: 2165-4743

DOI: 10.1109/APMC.2005.1606884

Publisher: IEEE

Conference Location: Suzhou

103. Attachment C-2 is evidence that the 2005 Asia-Pacific Microwave Conference was held December 4-7, 2005 in Suzhou, China. That EX1011, Jing, was added to the *IEEE Xplore* database March 20, 2006, more likely than not, EX1011, Jing, would have been immediately accessible and retrievable as of March 20, 2006 from *IEEE Xplore.*

104. Attachment C-3 is a true and correct copy of the *WorldCat* entry for. *2005 Asia-Pacific Microwave Conference Proceedings*, that I obtained by completing a search on *WorldCat* on May 11, 2025 by searching for libraries holding *2005 Asia-Pacific Microwave Conference Proceedings* near Cambridge, Massachusetts.

105. Attachment C-3 shows that *2005 Asia-Pacific Microwave Conference Proceedings* is the publication described in this *WorldCat* entry, as verified by

title*: 2005 Asia-Pacific Microwave Conference Proceedings;* publisher: IEEE, Piscataway, N.J., [2005]; and ISBN: 9780780394339, 078039433X.

106. *2005 Asia-Pacific Microwave Conference Proceedings* could have been located in *WorldCat* by searching for the title: *2005 Asia-Pacific Microwave Conference Proceedings; and/or* by searching the subject headings: *Microwave devices;* and/or *Microwaves,* among others.

107. When I searched *WorldCat* for library holdings of *2005 Asia-Pacific Microwave Conference Proceedings* in Cambridge, Massachusetts, among the 297 libraries owning the print version or providing access through *IEEE Xplore,* MIT Libraries was number one on the list.

108. Attachment C-4 is a download I made from the MIT Libraries OPAC (online catalog) on May 11, 2025. The monograph catalogued in this record is as verified by the OPAC record fields including title: *2005 Asia-Pacific Microwave Conference Proceedings*; publisher: IEEE; and ISBN: 0-7803-9433-X.

109. Evidence that the MIT Libraries received and holds Jing, EX1011, *2005 Asia-Pacific Microwave Conference Proceedings*, vol. 4 is shown in the OPAC record, Attachment C-4, in the area with the heading “Location Items” that

reads: *"on loan until 07/07/2025 08:00:00 (0 requests) v.4,* as shown below.

LOCATION ITEMS

Library Storage Annex
Out of library , Off Campus Collection ; TK7876.A75 2005

In transit until 05/10/2025 (1 request)
v.2

In transit until 05/10/2025 (1 request)
v.1

On loan until 07/07/2025 08:00:00 (0 requests)
v.4

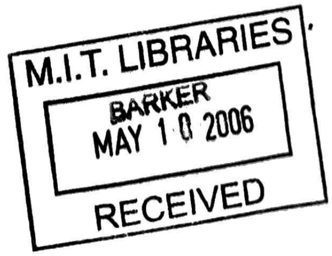
In transit until 05/10/2025 (1 request)
v.3

In transit until 05/10/2025 (1 request)
v.5

110. *2005 Asia-Pacific Microwave Conference Proceedings* could have been located in the MIT Libraries OPAC by searching for the title: *2005 Asia-Pacific Microwave Conference Proceedings* and/or subject headings: *Microwave devices* and/or *Microwaves*.

111. The process with which I am familiar at the MIT Libraries is that when a monograph is delivered to one of the libraries, it is stamped with the date and the name of the library. Jing, EX1011, has a date and name of the holding library, in this case, the Barker Library (the engineering library at MIT) with the date May 10, 2006. More likely than not, within two days it would have been

shelved in the Barker Library, and would then be accessible for a researcher, that is, May 12, 2006.



112. The print copy of Jing (EX1011) at the Barker Engineering Library at MIT would have been available for public access, more likely than not, by May 12, 2006.

113. Once Jing (EX1011) was entered into the general collection of the MIT Libraries, members of the public could access Jing (EX1011) in the Barker Engineering Library at MIT.

114. As I mentioned above in this section, a publication, in the case a monograph, is first received in the library's mailroom, and then is routed to the cataloging department. Cataloging description, etc., for Jing is retrieved from OCLC *WorldCat*, and entered into the holdings of the library and shown in the OPAC.

115. This process would have been completed by the date it was stamped as received from the cataloging department in the Barker Engineering Library at

MIT. The shelving of Jing would have been within a day but no more than two days, more likely than not, therefore by May 12, 2006.

3. Conclusion

116. EX1011, Jing, is an authentic document and would have been publicly accessible, more likely than not, in the Barker Engineering Library at MIT May 12, 2006. EX1011, Jing, would have been available through *IEEE Xplore* when it was added to the *IEEE Xplore* database, more likely than not, March 20, 2006.

D. EX1012: H. Nakano, Y. Sato, H. Mimaki and J. Yamauchi. "An Inverted FL Antenna for Dual-Frequency Operation," *IEEE Transactions on Antennas and Propagation*, vol. 53, no. 8, pp. 2417-2421, August 2005 ("Nakano")

117. I have been asked to opine on an article, authored by H. Nakano, Y. Sato, H. Mimaki and J. Yamauchi titled, "An Inverted FL Antenna for Dual-Frequency Operation," published in *IEEE Transactions on Antennas and Propagation*, vol. 53, no. 8, pp. 2417-2421, August 2005. ("Nakano")

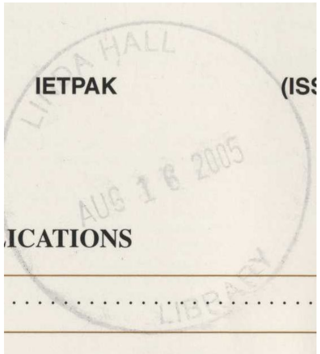
118. Within this declaration Nakano will indicate both the article titled "An Inverted FL Antenna for Dual-Frequency Operation," as well as the issue of *IEEE Transactions on Antennas and Propagation*, vol. 53, no. 8, August 2005, dependent upon context.

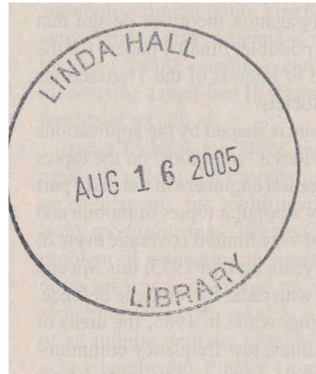
1. Authentication

119. I have evaluated the Nakano reference three ways: (1) by assessing the copy of Nakano (EX1012), provided to me by Petitioners' counsel and obtained by them from a digital copy available for a fee from *IEEE Xplore*; (2) by assessing scans of a print copy of Nakano owned by the Linda Hall Library, provided to me by the Linda Hall Library Document Delivery Service, Attachment D-1; and (3) by accessing and reviewing Nakano in digital format available to me as an emeritus faculty member through Purdue University Libraries, from *IEEE Xplore*, Attachment D-2.

120. EX1012, Nakano, has been provided to me by petitioners' counsel. I see no evidence that any alteration, deletion or addition of pages, etc., were made to EX1012.

121. Attachment D-1 was provided to me at my request on May 5, 2025, by Linda Hall Library Doc Services from the copy owned by the Linda Hall Library. Attachment D-1 includes scans of EX1012; cover of issue, *IEEE Transactions on Antennas and Propagation*, vol. 53, no. 8, August 2005, with a stamp that reads, "LINDA HALL AUG 16 2005 LIBRARY, as shown below; and ISSN 0018-926X; journal publication information pages [2] with the same date stamp as shown below; and the Nakano article, pages 2417-2421.





122. All identifying characteristics, such as stamps, on Attachment D-1, are consistent with library practice and procedure that I have observed during my career as a professional librarian. I have no cause for doubt about the authenticity or accuracy of these identifying attributes.

123. Attachment D-1 was found within the custody of a library, the Linda Hall Library, one of the most likely locations for an authentic document to be publicly accessible. Evidence of the ownership of Nakano by the Linda Hall Library will further be explored and detailed in the section below on public access (§IV.A.2).

124. Attachment D-2 is a download of Nakano that I made on May 9, 2025, from the *IEEE Xplore* database as an emeritus faculty member at Purdue University at the URL:

https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=1492584

Nakano is available from *IEEE Xplore* database for a fee at the URL:

https://ieeexplore.ieee.org/document/1492584

125. After my comparison between EX1012 and Attachment D-1 and Attachment D-2, I found no difference between EX1012, and Attachment D-1 and Attachment D-2.

126. Therefore, I affirm, after verifying EX1012, Nakano, against Attachment D-1, and Attachment D-2, that EX1012 is a complete and accurate version of 1012.

127. Therefore, with the evidence that Nakano is held in the Linda Hall Library (Attachment D-1), and accessing and retrieving Nakano from the *IEEE Xplore* database through the Purdue University Libraries (Attachment D-2), I have determined that EX1012 is an authentic document.

128. I conclude and affirm that EX1012 is an authentic document.

2. Public Accessibility

129. Attachment D-3 is a true and correct copy of the *WorldCat* entry for. *IEEE Transactions on Antennas and Propagation* that I obtained by completing a search on *WorldCat* on May 8, 2025 by searching for libraries holding this journal near Kansas City, Missouri, United States.

130. Attachment D-3 shows that *IEEE Transactions on Antennas and Propagation* is the journal associated with this *WorldCat* entry, as verified by title*: IEEE Transactions on Antennas and Propagation;* publisher: Institute of Electrical and Electronics Engineers (IEEE); and ISSN: 0018-926X.

131. *IEEE Transactions on Antennas and Propagation* could have been located in *WorldCat* by searching for the title of the journal: *IEEE Transactions on Antennas and Propagation;* and/or by searching the subject headings: *Antennas (Electronics); Radio Antennas*; and/or *Radio waves,* among others.

132. When I searched *WorldCat* for holdings of *IEEE Transactions on Antennas and Propagation* near Kansas City, Missouri, the Linda Hall Library was second on the list among the 892 libraries shown as holding *IEEE Transactions on Antennas and Propagation* near Kansas City, Missouri.

133. Attachment D-4 is a download I made from the Linda Hall Library OPAC (online catalog) on May 9, 2025. The journal catalogued in this record is *IEEE Transactions on Antennas and Propagation* as verified by the OPAC record fields including title: *IEEE Transactions on Antennas and Propagation*; publisher: Institution of Engineering and Technology: and ISSN: 0018-926X.

134. Evidence that the Linda Hall Library received and holds Nakano is shown in the OPAC record, Attachment D-4, in the area with the heading "Location" that reads: *"v.11 (1963 – Vol. 55 (2007),* as shown below, this is inclusive of volume 53, number 8, August 2005 .

LOCATIONS

Linda Hall Library
Available , Closed Stacks - Serials ; IEEE transactions on antennas and propagation.

Holdings:
Vol. 11(1963) - Vol. 55(2007);
Vol. 56 no. 1 (January 2008) -Vol. 56 no. 3 (March 2008)
Vol. 56 no. 6 (June 2008) -Vol. 56 no. 10 (October 2008)
Vol. 56 no. 12 (December 2008)
Vol. 57 no. 1 (January 2009) -Vol. 57 no. 12 (December 2009)

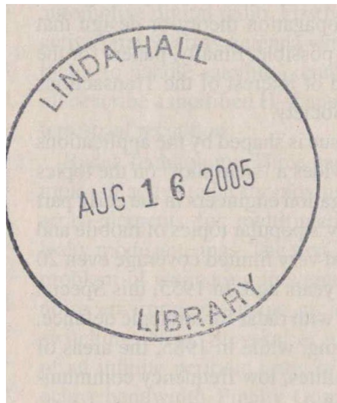
Holdings:
Vol. 11(1963) - Vol. 55(2007);

135. *IEEE Transactions on Antennas and Propagation* could have been located in the Linda Hall Library OPAC by searching for the title: *IEEE Transactions on Antennas and Propagation* and/or subject headings: *Radio; Radio -Antennas; Antennas (Electronics);* and/or *Radio Waves*.

136. Although the nominal publication date of *IEEE Transactions on Antennas and Propagation*, volume 53, number 8, is August 2005, from my experience and knowledge, it would not be inconsistent for a journal to be published, distributed to subscribers and libraries, and received and shelved in libraries prior to or after the nominal publication date.

137. For example, in this case, while the front cover of Nakano (EX1012) indicates that the nominal publication date of *IEEE Transactions on Antennas and Propagation*, volume 53, number 8, is August 2005, the date stamped on EX1012

– "Aug 16 2005," as shown below – indicates receipt of Nakano by the Linda Hall Library on August 16, 2005. A delay for distribution could be the result of various factors, for instance: editing or printing delays.



138. After a date stamp is applied to a holding, it is promptly sent for shelving. The amount of time it takes to be shelved (available to the public) varies depending on the nature of the item whether a monograph or a journal issue.

139. Monographs typically take longer than a journal issue because cataloguing of monographs is more work-intensive. A journal issue, such as Nakano, is, more likely than not, entered into the general collection, shelved, and publicly accessible within two to five days of application of a date stamp by a library.

140. Therefore, the print copy of Nakano (EX1012) at the Linda Hall Library would have been available for public access, more likely than not, by August 21, 2005.

141. Once Nakano (EX1012) was entered into the general collection of the Linda Hall Library, members of the public could access Nakano (EX1012) in the Reading Room.

142. As I mentioned above in this section, a publication is first received in the library's mailroom, and then is routed to an intake desk where it receives a date stamp. Thus, Nakano was received, more likely than not, in Linda Hall Library mailroom sometime before the stamp was applied on August 16, 2005.

143. The Linda Hall Library, more likely than not, received Nakano sometime before the stamp was applied on August 16, 2005, therefore, individual subscribers to *IEEE Transactions on Antennas and Propagation,* vol. 53, no. 8, August 2005 would also have, more likely than not, received Nakano before August 16, 2005.

3. Conclusion

144. Nakano (EX1012) is an authentic document and would have been publicly accessible, more likely than not, in the Linda Hall Library by August 21, 2005. Nakano also would have been received by subscribers, more likely than not, by August 16, 2005, just as it was received in the Linda Hall Library no later than, and likely earlier than, August 16, 2005.

V. RIGHT TO SUPPLEMENT

145. I reserve the right to supplement my opinions in the future to respond to any arguments that Patent Owner raises and to take into account new information as it becomes available to me.

VI. JURAT

146. I declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the full knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the U.S. Code.

Dated: May 13, 2025 By: James L. Mullins

James L. Mullins, Ph.D.

Attachment A-1

IEEE

MICROWAVE AND WIRELESS COMPONENTS LETTERS®

A PUBLICATION OF THE IEEE MICROWAVE THEORY AND TECHNIQUES SOCIETY

APRIL 2004 VOLUME 14 NUMBER 4 IMWCBJ (ISSN 1531-1309)

LETTERS

IEEE

Design of an Internal Quad-Band Antenna for Mobile Phones

Pascal Ciais, Robert Staraj, Georges Kossiavas, and Cyril Luxey

***Abstract*—This letter presents the design of a compact Planar Inverted-F Antenna (PIFA) suitable for cellular telephone applications. The quarter-wavelength antenna combines the use of a slot, shorted parasitic patches and capacitive loads to achieve multi-band operation. The commercial electromagnetic software IE3D is used to design and optimize the structure. The resulting antenna can operate from 880 to 960 MHz and 1710 to 2170 MHz covering GSM, DCS, PCS, and UMTS standards with a VSWR better than 2.5. Good agreement is found between simulated and measured results.**

***Index Terms*—Handset antennas, multiband antennas, planar inverted-F antennas (PIFAs), small antennas.**

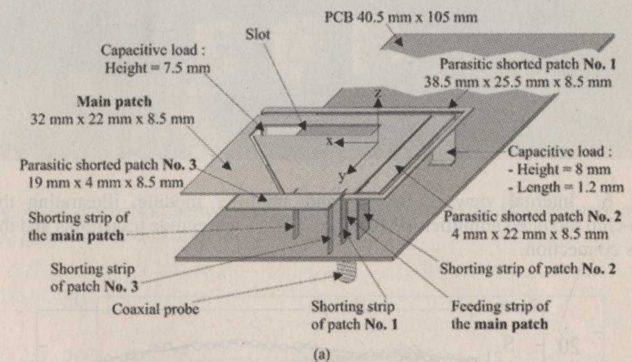
I. INTRODUCTION

WITH the rapid progress in new communication standards, miniature multiband internal antennas are needed for modern mobile handsets [1]–[3]. Several techniques applied simultaneously are thus necessary to reduce the size of these antennas while maintaining good multiband/wideband performance.

The antenna presented in this letter combines several of these techniques. The main resonator is a dual-band PIFA antenna tuned to operate at center frequencies of 935 MHz and 1930 MHz. The introduction of a slot into this element allows a frequency decrease of its fundamental resonance while the use of an end positioned capacitive load allows its higher order modes to be decreased in frequency (Fig. 1) [4]. Instead of the previously reported tunable scheme [2], the addition of three quarter-wavelength parasitic elements is used here to create new resonances [5]–[7] and thus enlarge both lower and upper impedance bandwidth. These new resonances are tuned thanks to a lengthening by capacitive loads [7]. This antenna covers the GSM standard (Global System for Mobile communications, 880–960 MHz) with a VSWR (Voltage Standing Wave Ratio) better than 2.5 and also the DCS (Digital Communication System, 1710–1880 MHz), PCS (Personal Communication Services, 1850–1990 MHz) and UMTS (Universal Mobile Telecommunications System, 1920–2170 MHz) standards with a VSWR less than 2.

II. ANTENNA STRUCTURE AND DESIGN RULES

The antenna consists of a main patch with three additional parasitic elements placed on the corner of a ground plane



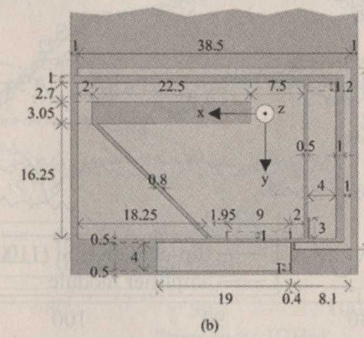


Fig. 1. Configuration of the quad-band antenna. (a) Side view. (b) Top view : all dimensions are in millimeter.

whose size is representative of the Printed Circuit Board (PCB) of a typical mobile phone: 40.5 mm × 105 mm (Fig. 1). The PCB size, especially its length, has a strong influence on the performances of mobile phone antennas. In our case, the chosen length is not the best choice for an optimum GSM bandwidth (around 130 mm [9]–[11]) or an optimum DCS bandwidth (around 70 mm [9]–[11]) but it will equally helps in these both bands for an efficient antenna-chassis combination. The dielectric between all patches and the PCB is air and the separation distance is 8.5 mm.

The main quarter-wavelength patch is coaxially fed via a metallic strip. The first objective is to get a proper resonance in the GSM band, where the approximate formula: $f_r = c/4(L+H)$, is used as a starting rule for the design of the patch (with f_r = resonant frequency of the patch, c = velocity of light in free space, L = average length of the patch, and H = height of the patch). The analytical length of a 8.5 mm height quarter-wavelength resonator is then found to be 71.7 mm at 935 MHz in the GSM band. This length can be slightly reduced by using a partial shorting strip instead of a plain shorting wall. Moreover, it has been previously shown that both the antenna with its feeding and shorting pins always have to be positioned at the top of the PCB to obtain an efficient

Manuscript received July 17, 2003; revised November 21, 2003. This work was supported by France Telecom R&D under Contract 424 76-344.

The authors are with the Laboratoire d'Electronique, Antennes et Télécommunications, Université de Nice-Sophia Antipolis/UMR-CNRS 6071, 06560 Valbonne, France (e-mail: ciaisp@elec.unice.fr).

Digital Object Identifier 10.1109/LMWC.2004.825186

antenna-chassis combination, especially maximum bandwidth behavior [8]–[11]. In such a configuration, the matching of the antenna to a 50 Ω source is not so difficult to achieve since the 50 Ω input impedance point is not spatially far from the shorting strip. However, due to its intrinsic properties, the design at 935 MHz of a rectangular quarter-wavelength patch with its length aligned with the PCB length, will only lead to an odd number of higher resonance frequencies namely 2805 MHz (3 f_r), 4675 MHz (5 f_r), and so on. As our main element need to resonate in the 1710–2170 MHz band, we need to decrease the working frequency of the 3rd higher mode of this structure. It has been successfully demonstrated in [9] that adding a capacitive load to the structure will result in a decrease of the frequency of its higher modes. This can be achieved by folding the patch over on itself. The value of this capacitance can be controlled by increasing or decreasing the metal facing surfaces. However, this folding operation also reduces the bandwidth of the antenna due to an inherent increase of its total quality factor Q [12].

Three parasitic elements have to be added to the main patch to achieve our desired multiband goal. These elements are chosen quarter-wavelength type, each connected to the ground plane by metallic strips and located near the main patch in order to be correctly electromagnetically excited. Capacitive loads can be added to these parasitic patches by vertically folding their strip ends. Hence, the electrical lengths of these resonators are artificially increased without enlarging the whole antenna size. A first parasitic patch have to be added to enlarge the GSM bandwidth (no. 1 on Fig. 1), its theoretical quarter-wavelength is found to be 76 mm at 888 MHz. Two others parasitic patches must be added to increase the upper bandwidth (no. 2 and no. 3 on Fig. 1). Their theoretical lengths are 34.1 mm at 1760 MHz and 26.9 mm at 2120 MHz.

III. Results

With these empirical design rules, a dual-band patch antenna was first designed and optimized using a simulation tool based on the method of moments : IE3D [13]. Parasitic patches no. 2 and no. 3 were then separately and simultaneously added to this main patch. At last, parasitic patch no. 1 was built to achieve the final goal. All structures have been fine tuned to achieve the best possible coupling between the resonances i.e the largest possible bandwidths. This tuning was made by slightly changing the main dimensions of the parasitic patches and/or their gaps with the main patch. All the optimized dimensions of each stage are not listed here for brevity. Fig. 2 shows the simulated VSWR of the main patch with and without parasitic shorted patches no. 2 and no. 3. It is seen on this graph that the main patch alone has two resonances in the GSM band and around 2 GHz with both small bandwidths. The VSWR curves of the main patch with the addition of only one parasitic patch (no. 2 or no. 3) are also plotted on this graph. In both cases, it increases the upper bandwidth of the first antenna in two different ways: parasitic no. 2 works below the 3rd resonance of the main patch while parasitic No. 3 works above. The simulated VSWR of the main plate with the simultaneous addition of these two shorted patches is also plotted on Fig. 2. This structure has now an upper bandwidth of 470 MHz (1705–2175 MHz)

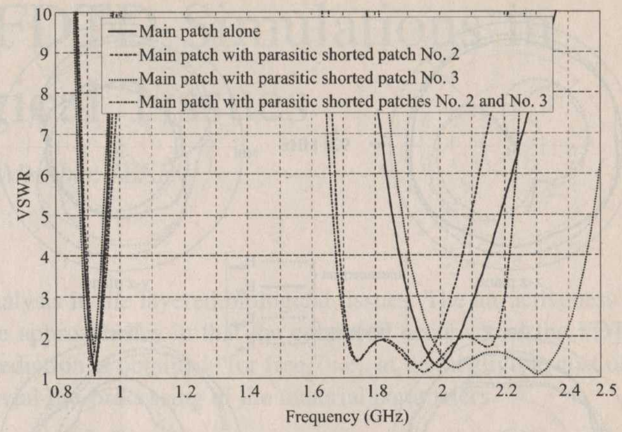


Fig. 2. Simulated VSWR of the main patch with and without parasitic shorted patches no. 2 and no. 3.

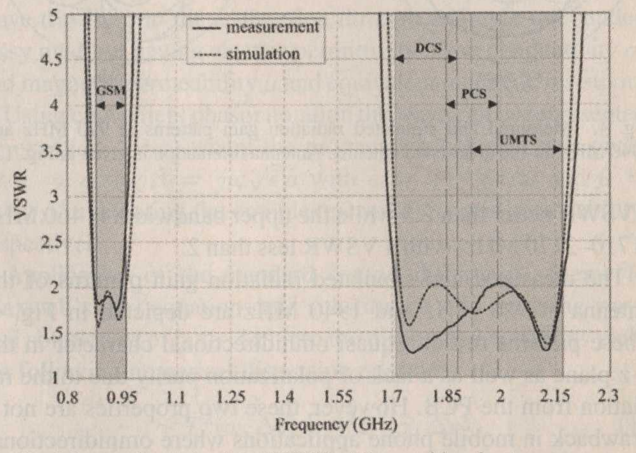


Fig. 3. Measured and simulated VSWR of the quad-band antenna.

with a VSWR less than 2 covering the DCS, PCS and UMTS standards but the lower bandwidth of 40 MHz (905–945 MHz) with a VSWR less than 2.5 is clearly insufficient to cover the entire GSM band. The performances of the main antenna with parasitics no. 2 and no. 3 shows that an additional parasitic element no. 1 is needed to increase the low part of the GSM band. Fig. 3 compares the simulated and measured VSWR of the final quad-band antenna (dimensions 38.5 mm × 28.5 mm × 8.5 mm). The step by step optimization of the structure resulted in a folded dual-band patch antenna of dimensions 32 mm × 22 mm × 8.5 mm with a strong quasilocalized capacitive load at its end and an average quarter-wavelength length of 72.2 mm that is very close to the theoretical value of 71.7 mm. The physical length of parasitic patch no. 1 is 77.6 mm, compared with the theoretical quarter-wavelength of 76 mm at 888 MHz. Capacitive loads were added to the parasitic patches no. 1 and no. 2 by vertically folding their strip ends. Physical lengths of elements no. 2 and no. 3 are respectively 31.2 mm and 19 mm to be compared with the theoretical quarter-wavelengths of 34.1 mm at 1760 MHz and 26.9 mm at 2120 MHz. The small discrepancies between these values comes from the theoretical formula which doesn't take into account localized and distributed capacitive loading effects. This capacitive effect is very strong in the case of parasitic element no. 3 where two high impedance portions of metal face each others. A good agreement between theoretical and experimental results is observed. The measured lower bandwidth is 90 MHz (870–960 MHz) with

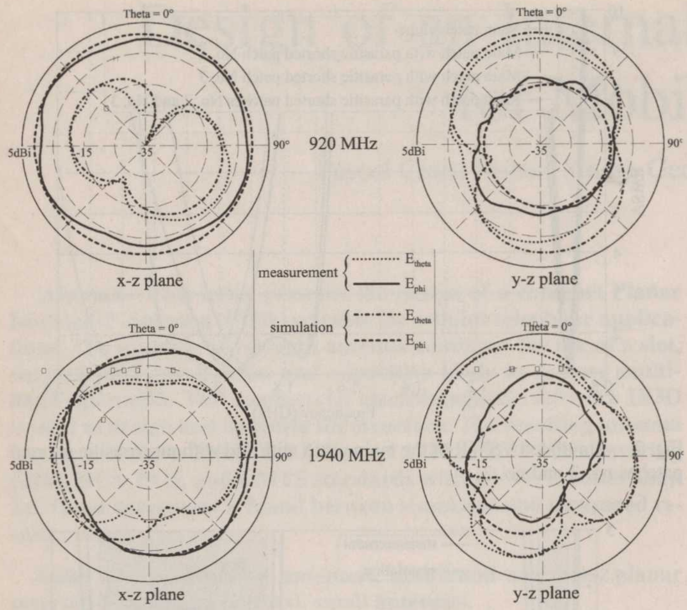


Fig. 4. Measured and simulated radiation gain patterns at 920 MHz and 1940 MHz for the quad-band antenna. Antenna orientation is given in Fig. 1.

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The measured and simulated radiation gain patterns of the antenna at 920 MHz and 1940 MHz are depicted in Fig. 4. These patterns reveal a quasi omnidirectional character in the x-z plane as well as a lack of polarization purity due to the radiation from the PCB. However, these two properties are not a drawback in mobile phone applications where omnidirectional radiation patterns as well as both vertical and horizontal electromagnetic field polarization occur in urban environments [14]. These omnidirectional patterns are due to the dipole-like behavior of the structure coming from the antenna-chassis combination : due to the in-phase currents flowing on the PCB in the GSM band, quasi perfect omnidirectional pattern is seen while some directivity appears at 1940 MHz in both planes since the length of the PCB is now larger than half the wavelength. Some discrepancies are found between theoretical and experimental far-field patterns. The small ripple seen in the measured curves comes principally from our measurement setup, especially from the radiation contribution of the feed cable of the antenna : in small antenna measurements, it is difficult to correctly choke the feed cable to avoid currents flowing on it [15], [16]. The measured maximum gains for the antenna are 1 dBi at 920 MHz and 3.3 dBi at 1940 MHz while the simulated are respectively 1.3 dBi and 3.5 dBi. The small discrepancies between these values are mainly attributed to the dielectric losses of the plastic support used in our radiation pattern measurement setup to maintain the antenna.

The efficiency of the structure, defined as the total radiated power divided by the incident power at the feed, takes into account reflection losses due to the mismatch between the coaxial probe and the antenna as well as ohmic losses. The computed efficiency was respectively above 69% and 74% in the GSM and DCS/PCS/UMTS bands which is suitable for mobile phone communication terminals.

IV. Conclusion

A compact multiband PIFA antenna with parasitic elements was designed and placed on a realistic PCB ground plane. This new structure uses various techniques of miniaturization to achieve low return loss in both GSM and DCS/PCS/UMTS bands. The quasi omnidirectional gain radiation pattern characteristics with good efficiency over the covered frequency bands make this antenna suitable for mobile phone applications. Further work will be concentrated on the coverage of new 2.4 GHz and 5.2 GHz standards.

Acknowledgment

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References

[1] Y.-X. Guo, M. Y. W. Chia, and Z. N. Chen, "Miniature built-in quad band antennas for mobile handsets," *IEEE Antennas Wireless Propagat. Lett.*, vol. 2, pp. 30–32, 2003.

[2] N. C. Karmakar, P. Hendro, and L. S. Firmansyah, "Shorting strap tunable single feed dual-band PIFA," *IEEE Microwave Wireless Comp. Lett.*, vol. 13, pp. 13–15, Jan. 2003.

[3] I. Ang, Y.-X. Guo, and Y. W. Chia, "Compact internal quad-band antenna for mobile phones," *Microw. Opt. Technol. Lett.*, vol. 38, no. 3, pp. 217–223, Aug. 2003.

[4] P. Salonen, M. Keskilammi, and M. Kivikoski, "New slot configurations for dual-band planar inverted-F antenna," *Microw. Opt. Technol. Lett.*, vol. 28, no. 5, pp. 293–298, Mar. 2001.

[5] Y. J. Wang, C. K. Lee, W. J. Koh, and Y. B. Gan, "Design of small and broad-band internal antennas for IMT-2000 mobile handsets," *IEEE Trans. Microw. Theory Tech.*, vol. 49, no. 8, pp. 1398–1403, Aug. 2001.

[6] C. T. P. Song, P. S. Hall, H. Ghafouri-Shiraz, and D. Wake, "Triple band planar inverted F antennas for handheld devices," *Electron. Lett.*, vol. 36, no. 2, pp. 112–114, Jan. 2000.

[7] J. Ollikainen, O. Kivekäs, A. Toropainen, and P. Vainikainen, "Internal dual-band patch antenna for mobile phones," in *Proc. Millennium Conf. Antennas Propagat.*, Davos, Switzerland, Apr. 2000, SP-444, session 3A9.

[8] M. Geissler, D. Heberling, and I. Wolff, "Properties of integrated handset antennas," in *Proc. Millenium Conf. Antennas Propagat.*, Davos, Switzerland, Apr. 2000, SP-444, session 5A5.

[9] D. Manteuffel, A. Bahr, D. Heberling, and I. Wolff, "Design considerations for integrated mobile phone antennas," in *Proc. 11th Int. Conf. Antennas Propagat.*, Apr. 2001, pp. 252–256.

[10] O. Kivekäs, J. Ollikainen, T. Lehtiemi, and P. Vainikainen, "Effect of the chassis length on the bandwidth, SAR, and efficiency of internal mobile phone antennas," *Microw. Opt. Technol. Lett.*, vol. 36, no. 6, pp. 457–462, Mar. 2003.

[11] P. Vainikainen, J. Ollikainen, O. Kivekäs, and I. Kelander, "Resonator-based analysis of the combination of mobile handset antenna and chassis," *IEEE Trans. Antennas Propagat.*, vol. 50, pp. 1433–1444, Oct. 2002.

[12] C. R. Rowell and R. D. Murch, "A capacitively loaded PIFA for compact mobile telephone handsets," *IEEE Trans. Antennas Propagat.*, vol. 45, pp. 837–842, May 1997.

[13] *IE3D, Release 9.33*, Zeland Software, Inc., 2002.

[14] K. Sulonen and P. Vainikainen, "Handset antenna evaluation based on measured distributions," in *Proc. IEEE Instrumentation and Measurement Technology Conf.*, Budapest, Hungary, May. 2001, pp. 519–524.

[15] J. Haley, T. Moore, and J. T. Bernhard, "Experimental investigation of antenna-handset-feed interaction during wireless product testing," *Microw. Opt. Technol. Lett.*, vol. 34, no. 3, pp. 169–172, Aug. 2002.

[16] C. Ilchen, J. Ollikainen, and P. Vainikainen, "Reducing the influence of feed cables on small antenna measurements," *Electron. Lett.*, vol. 35, no. 15, pp. 1212–1214, July 1999.

Attachment A-2

Design of an Internal Quad-Band Antenna for Mobile Phones

Pascal Ciais, Robert Staraj, Georges Kossiavas, and Cyril Luxey

***Abstract*—This letter presents the design of a compact Planar Inverted-F Antenna (PIFA) suitable for cellular telephone applications. The quarter-wavelength antenna combines the use of a slot, shorted parasitic patches and capacitive loads to achieve multi-band operation. The commercial electromagnetic software IE3D is used to design and optimize the structure. The resulting antenna can operate from 880 to 960 MHz and 1710 to 2170 MHz covering GSM, DCS, PCS, and UMTS standards with a VSWR better than 2.5. Good agreement is found between simulated and measured results.**

***Index Terms*—Handset antennas, multiband antennas, planar inverted-F antennas (PIFAs), small antennas.**

I. INTRODUCTION

WITH the rapid progress in new communication standards, miniature multiband internal antennas are needed for modern mobile handsets [1]–[3]. Several techniques applied simultaneously are thus necessary to reduce the size of these antennas while maintaining good multiband/wideband performance.

The antenna presented in this letter combines several of these techniques. The main resonator is a dual-band PIFA antenna tuned to operate at center frequencies of 935 MHz and 1930 MHz. The introduction of a slot into this element allows a frequency decrease of its fundamental resonance while the use of an end positioned capacitive load allows its higher order modes to be decreased in frequency (Fig. 1) [4]. Instead of the previously reported tunable scheme [2], the addition of three quarter-wavelength parasitic elements is used here to create new resonances [5]–[7] and thus enlarge both lower and upper impedance bandwidth. These new resonances are tuned thanks to a lengthening by capacitive loads [7]. This antenna covers the GSM standard (Global System for Mobile communications, 880–960 MHz) with a VSWR (Voltage Standing Wave Ratio) better than 2.5 and also the DCS (Digital Communication System, 1710–1880 MHz), PCS (Personal Communication Services, 1850–1990 MHz) and UMTS (Universal Mobile Telecommunications System, 1920–2170 MHz) standards with a VSWR less than 2.

II. ANTENNA STRUCTURE AND DESIGN RULES

The antenna consists of a main patch with three additional parasitic elements placed on the corner of a ground plane whose size is representative of the Printed Circuit Board (PCB) of a typical mobile phone: 40.5 mm $\times$ 105 mm (Fig. 1). The PCB size, especially its length, has a strong influence on the performances of mobile phone antennas. In our case, the chosen length is not the best choice for an optimum GSM bandwidth (around 130 mm [9]–[11]) or an optimum DCS bandwidth (around 70 mm [9]–[11]) but it will equally helps in these both bands for an efficient antenna-chassis combination. The dielectric between all patches and the PCB is air and the separation distance is 8.5 mm.

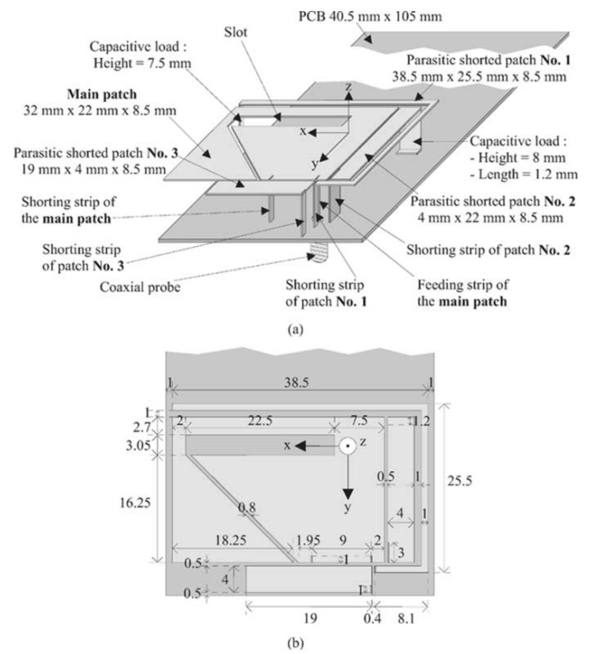

Fig. 1. Configuration of the quad-band antenna. (a) Side view. (b) Top view : all dimensions are in millimeter.

The main quarter-wavelength patch is coaxially fed via a metallic strip. The first objective is to get a proper resonance in the GSM band, where the approximate formula: $f_r = c/4(L + H)$, is used as a starting rule for the design of the patch (with $f_r = \text{resonant frequency}$ of the patch, $c = \text{velocity of light}$ in free space, $L = \text{average length}$ of the patch, and $H = \text{height}$ of the patch). The analytical length of a 8.5 mm height quarter-wavelength resonator is then found to be 71.7 mm at 935 MHz in the GSM band. This length can be slightly reduced by using a partial shorting strip instead of a plain shorting wall. Moreover, it has been previously shown that both the antenna with its feeding and shorting pins always have to be positioned at the top of the PCB to obtain an efficient

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antenna-chassis combination, especially maximum bandwidth behavior [8]–[11]. In such a configuration, the matching of the antenna to a 50 Ω source is not so difficult to achieve since the 50 Ω input impedance point is not spatially far from the shorting strip. However, due to its intrinsic properties, the design at 935 MHz of a rectangular quarter-wavelength patch with its length aligned with the PCB length, will only lead to an odd number of higher resonance frequencies namely 2805 MHz (3 f_r), 4675 MHz (5 f_r), and so on. As our main element need to resonate in the 1710–2170 MHz band, we need to decrease the working frequency of the 3rd higher mode of this structure. It has been successfully demonstrated in [9] that adding a capacitive load to the structure will result in a decrease of the frequency of its higher modes. This can be achieved by folding the patch over on itself. The value of this capacitance can be controlled by increasing or decreasing the metal facing surfaces. However, this folding operation also reduces the bandwidth of the antenna due to an inherent increase of its total quality factor Q [12].

Three parasitic elements have to be added to the main patch to achieve our desired multiband goal. These elements are chosen quarter-wavelength type, each connected to the ground plane by metallic strips and located near the main patch in order to be correctly electromagnetically excited. Capacitive loads can be added to these parasitic patches by vertically folding their strip ends. Hence, the electrical lengths of these resonators are artificially increased without enlarging the whole antenna size. A first parasitic patch have to be added to enlarge the GSM bandwidth (no. 1 on Fig. 1), its theoretical quarter-wavelength is found to be 76 mm at 888 MHz. Two others parasitic patches must be added to increase the upper bandwidth (no. 2 and no. 3 on Fig. 1). Their theoretical lengths are 34.1 mm at 1760 MHz and 26.9 mm at 2120 MHz.

III. Results

With these empirical design rules, a dual-band patch antenna was first designed and optimized using a simulation tool based on the method of moments : IE3D [13]. Parasitic patches no. 2 and no. 3 were then separately and simultaneously added to this main patch. At last, parasitic patch no. 1 was built to achieve the final goal. All structures have been fine tuned to achieve the best possible coupling between the resonances i.e the largest possible bandwidths. This tuning was made by slightly changing the main dimensions of the parasitic patches and/or their gaps with the main patch. All the optimized dimensions of each stage are not listed here for brevity. Fig. 2 shows the simulated VSWR of the main patch with and without parasitic shorted patches no. 2 and no. 3. It is seen on this graph that the main patch alone has two resonances in the GSM band and around 2 GHz with both small bandwidths. The VSWR curves of the main patch with the addition of only one parasitic patch (no. 2 or no. 3) are also plotted on this graph. In both cases, it increases the upper bandwidth of the first antenna in two different ways: parasitic no. 2 works below the 3rd resonance of the main patch while parasitic No. 3 works above. The simulated VSWR of the main plate with the simultaneous addition of these two shorted patches is also plotted on Fig. 2. This structure has now an upper bandwidth of 470 MHz (1705–2175 MHz)

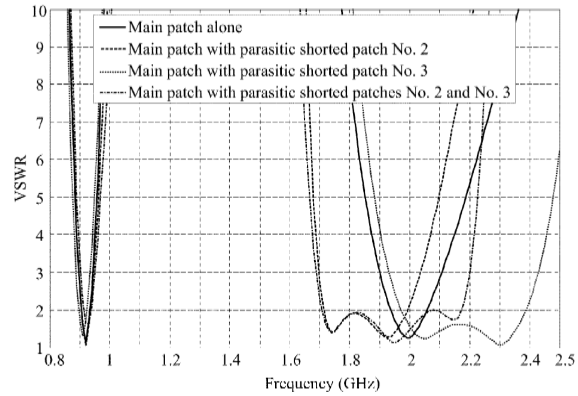

Fig. 2. Simulated VSWR of the main patch with and without parasitic shorted patches no. 2 and no. 3.

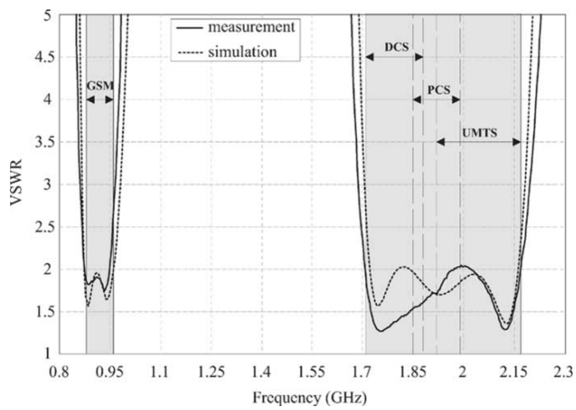

Fig. 3. Measured and simulated VSWR of the quad-band antenna.

with a VSWR less than 2 covering the DCS, PCS and UMTS standards but the lower bandwidth of 40 MHz (905–945 MHz) with a VSWR less than 2.5 is clearly insufficient to cover the entire GSM band. The performances of the main antenna with parasitics no. 2 and no. 3 shows that an additional parasitic element no. 1 is needed to increase the low part of the GSM band. Fig. 3 compares the simulated and measured VSWR of the final quad-band antenna (dimensions 38.5 mm $\times$ 28.5 mm $\times$ 8.5 mm). The step by step optimization of the structure resulted in a folded dual-band patch antenna of dimensions 32 mm $\times$ 22 mm $\times$ 8.5 mm with a strong quasilocalized capacitive load at its end and an average quarter-wavelength length of 72.2 mm that is very close to the theoretical value of 71.7 mm. The physical length of parasitic patch no. 1 is 77.6 mm, compared with the theoretical quarter-wavelength of 76 mm at 888 MHz. Capacitive loads were added to the parasitic patches no. 1 and no. 2 by vertically folding their strip ends. Physical lengths of elements no. 2 and no. 3 are respectively 31.2 mm and 19 mm to be compared with the theoretical quarter-wavelengths of 34.1 mm at 1760 MHz and 26.9 mm at 2120 MHz. The small discrepancies between these values comes from the theoretical formula which doesn't take into account localized and distributed capacitive loading effects. This capacitive effect is very strong in the case of parasitic element no. 3 where two high impedance portions of metal face each others. A good agreement between theoretical and experimental results is observed. The measured lower bandwidth is 90 MHz (870–960 MHz) with

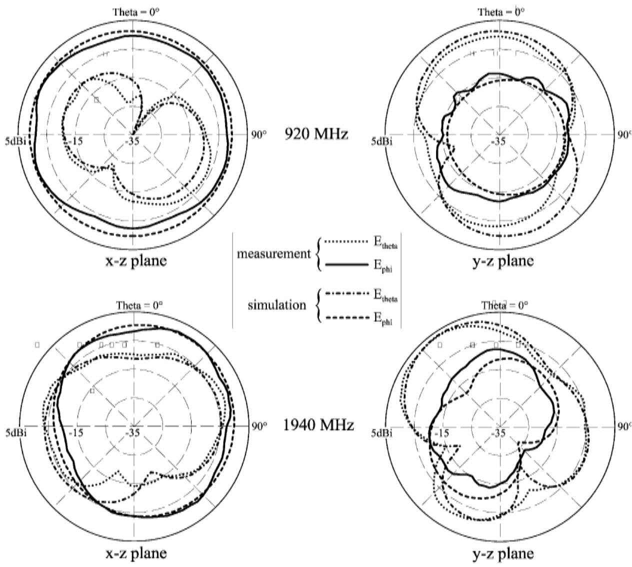

Fig. 4. Measured and simulated radiation gain patterns at 920 MHz and 1940 MHz for the quad-band antenna. Antenna orientation is given in Fig. 1.

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References

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[3] I. Ang, Y.-X. Guo, and Y. W. Chia, "Compact internal quad-band antenna for mobile phones," *Microw. Opt. Technol. Lett.*, vol. 38, no. 3, pp. 217–223, Aug. 2003.

[4] P. Salonen, M. Keskilammi, and M. Kivikoski, "New slot configurations for dual-band planar inverted-F antenna," *Microw. Opt. Technol. Lett.*, vol. 28, no. 5, pp. 293–298, Mar. 2001.

[5] Y. J. Wang, C. K. Lee, W. J. Koh, and Y. B. Gan, "Design of small and broad-band internal antennas for IMT-2000 mobile handsets," *IEEE Trans. Microw. Theory Tech.*, vol. 49, no. 8, pp. 1398–1403, Aug. 2001.

[6] C. T. P. Song, P. S. Hall, H. Ghafouri-Shiraz, and D. Wake, "Triple band planar inverted F antennas for handheld devices," *Electron. Lett.*, vol. 36, no. 2, pp. 112–114, Jan. 2000.

[7] J. Ollikainen, O. Kivekäs, A. Toropainen, and P. Vainikainen, "Internal dual-band patch antenna for mobile phones," in *Proc. Millennium Conf. Antennas Propagat.*, Davos, Switzerland, Apr. 2000, SP-444, session 3A9.

[8] M. Geissler, D. Heberling, and I. Wolff, "Properties of integrated handset antennas," in *Proc. Millenium Conf. Antennas Propagat.*, Davos, Switzerland, Apr. 2000, SP-444, session 5A5.

[9] D. Manteuffel, A. Bahr, D. Heberling, and I. Wolff, "Design considerations for integrated mobile phone antennas," in *Proc. 11th Int. Conf. Antennas Propagat.*, Apr. 2001, pp. 252–256.

[10] O. Kivekäs, J. Ollikainen, T. Lehtiemi, and P. Vainikainen, "Effect of the chassis length on the bandwidth, SAR, and efficiency of internal mobile phone antennas," *Microw. Opt. Technol. Lett.*, vol. 36, no. 6, pp. 457–462, Mar. 2003.

[11] P. Vainikainen, J. Ollikainen, O. Kivekäs, and I. Kelander, "Resonator-based analysis of the combination of mobile handset antenna and chassis," *IEEE Trans. Antennas Propagat.*, vol. 50, pp. 1433–1444, Oct. 2002.

[12] C. R. Rowell and R. D. Murch, "A capacitively loaded PIFA for compact mobile telephone handsets," *IEEE Trans. Antennas Propagat.*, vol. 45, pp. 837–842, May 1997.

[13] *IE3D, Release 9.33*, Zeland Software, Inc., 2002.

[14] K. Sulonen and P. Vainikainen, "Handset antenna evaluation based on measured distributions," in *Proc. IEEE Instrumentation and Measurement Technology Conf.*, Budapest, Hungary, May. 2001, pp. 519–524.

[15] J. Haley, T. Moore, and J. T. Bernhard, "Experimental investigation of antenna-handset-feed interaction during wireless product testing," *Microw. Opt. Technol. Lett.*, vol. 34, no. 3, pp. 169–172, Aug. 2002.

[16] C. Ilchen, J. Ollikainen, and P. Vainikainen, "Reducing the influence of feed cables on small antenna measurements," *Electron. Lett.*, vol. 35, no. 15, pp. 1212–1214, July 1999.

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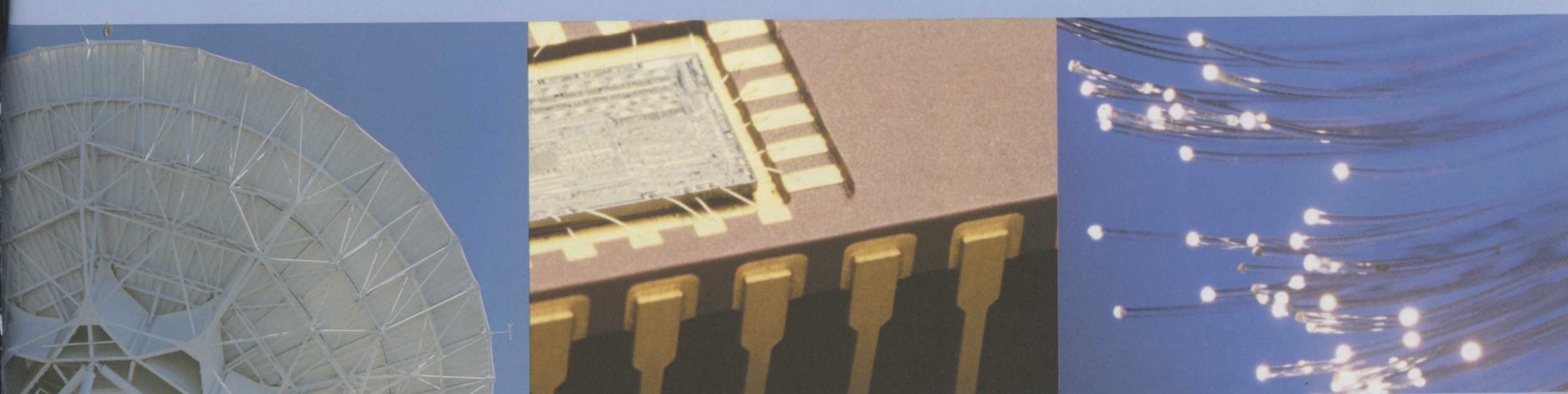

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(continued overleaf)

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References

1 Yang, C.Y., and Liu, S.I.: 'Fast-switching frequency synthesizer with a discriminator-aided phase detector', *IEEE J. Solid-State Circuits*, 2000, **35**, (10), pp. 1445–1452

2 Shu, K., Sánchez-Sinencio, E., and Embabi, S.H.K.: 'A 2.4-GHz monolithic fractional-N frequency synthesizer with robust phase-switching prescaler and loop capacitance multiplier', *IEEE J. Solid-State Circuits*, 2003, **38**, (6), pp. 866–874

3 Larsson, P.: 'Reduced pull-in time of phase-locked loops using a simple nonlinear phase detector', *IEE Proc., Commun.*, 1995, **142**, (4), pp. 221–226

4 Sie, M., Cibiel, G., Tournier, E., Plana, R., and Graffeuil, J.: 'High-speed, spurious-free sequential phase frequency detector and dual-modulus prescalers for RF frequency synthesis'. Proc. Symp. Radio Frequency Integrated Circuits, Philadelphia, PA, USA, June 2003, pp. 679–682

Compact internal multiband antenna for mobile phone and WLAN standards

P. Ciais, R. Staraj, G. Kossiavas and C. Luxey

A novel internal planar inverted-F antenna (PIFA) suitable for handset terminals is presented. The structure combines shorted parasitic patches, capacitive loads and slots to achieve multiband operation. This compact antenna operates in the GSM, DCS, PCS, UMTS, HIPERLAN/2 and IEEE 802.11a bands within 2.5:1 voltage standing wave ratio (VSWR) and with good efficiency.

Introduction: The rapid increase of communication standards has led to a great demand in designing multiband antennas for handset devices. Internal planar inverted-F antennas (PIFAs) are very suitable in such applications since they are compact, low profile and easy to manufacture. Starting with a main shorted resonator, several techniques must be simultaneously applied to achieve multiband/wideband performances: addition of parasitic shorted patches and capacitive loads, and use of slots. Recently, quad-band antennas for mobile phones [1–4] and dual-band antennas for wireless local area network (WLAN) operations [5, 6] have been successfully designed. However, none of these antennas can simultaneously cover all the following communication standards: GSM (Global System for Mobile communications, 880–960 MHz), DCS (Digital Communication System, 1710–1880 MHz), PCS (Personal Communication Services, 1850–1990 MHz), UMTS (Universal Mobile Telecommunications System, 1920–2170 MHz), HIPERLAN/2 in Europe (HIgh PERformance Local Area Network—Type 2, 5150–5350/5470–5725 MHz) and IEEE 802.11a in the USA (Institute of Electrical and Electronics Engineers, 5150–5350/5725–5825 MHz). The antenna presented in this Letter is based on the quad-band structure reported in [4], and another technique is applied here to achieve the tuning of its higher-order resonances in the WLAN band.

Antenna structure and design rules: The antenna consists of a main quarter-wavelength patch, with three additional parasitic elements (Fig. 1). This radiating structure has dimensions of 38.5 × 28.5 × 8.5 mm and is placed on the corner of a ground plane having a size approximately equal to that of the printed circuit board (PCB) of a typical mobile phone, i.e. 40.5 × 105 mm. The dielectric between all patches and the PCB is air, and its thickness is 8.5 mm. The formula

$$f_r = \frac{c}{4(L+H)}$$

is used as a starting rule for choosing the length of the main patch (where f_r = resonant frequency of the patch in the GSM band, c = velocity of light in free space, L = average length of the patch and H = height of the patch). The patch is coaxially fed via a metallic strip and its quarter-wavelength character is obtained thanks to a shorting metallic strip. Moreover, a slot is etched in this patch to obtain both a longer average current path and a strong capacitive effect between its metal facing surfaces to achieve a frequency decrease of its fundamental and higher-order mode resonances [4]. The optimisation is done using the commercial simulation tool IE3D, version 10.06, which is based on the method of moments. The resulting structure is a well-matched antenna in the GSM and the 2 GHz bands. Three quarter-wavelength type, parasitic shorted patches are then added to widen these bandwidths. Each one is connected to the ground plane by metallic strips and located near the main patch in order to be efficiently electromagnetically coupled. Parasitic elements 2 and 3 increase the upper bandwidth of the main patch, respectively, below and above its third resonance at 2 GHz. Parasitic element 1 increases the lower part of the GSM band. Vertically folding the end strips of parasitics 1 and 2 creates a capacitive loading and artificially increases their electrical lengths. The optimised structure of this second step is a quad-band GSM/DCS/PCS/UMTS antenna with a VSWR better than 2.5 [4]. The last step is now to cover the two WLAN standards without altering the previous resonances.

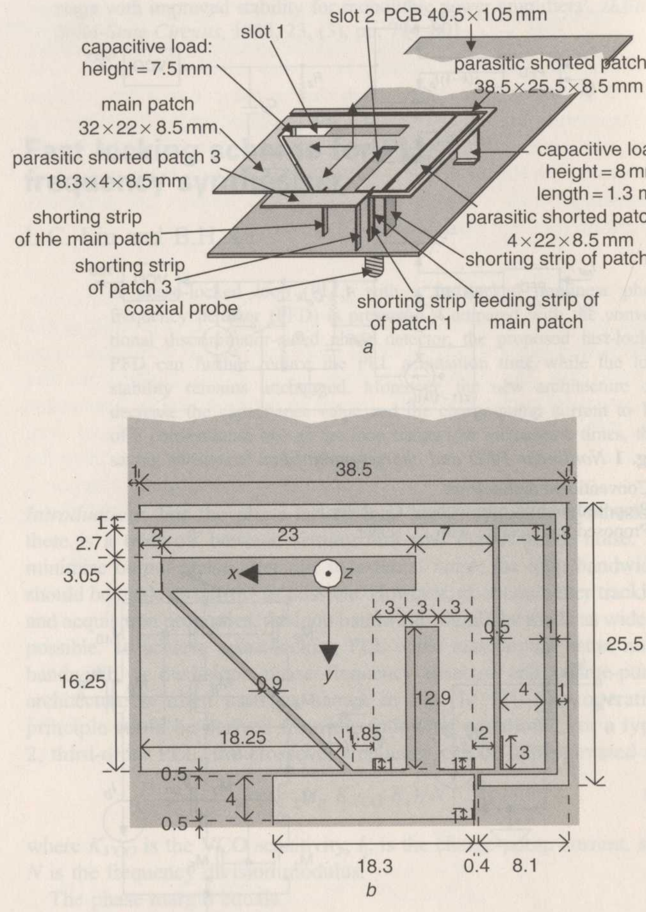

Fig. 1 *3D view of multiband antenna*

a 3D view *b* Top view (all dimensions in millimetres)

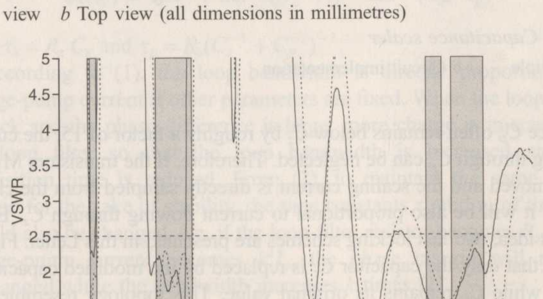

Fig. 2 *Measured and simulated VSWR of multiband antenna*

Standards bandwidth requirement in grey

—— measurement ------ simulation

A meticulous simulated parametric study was conducted on each patch by independently changing their physical parameters in order to identify and control their higher-order modes around 5 GHz. It was found that the tuning and matching process of the resonances of all the parasitics led to only small modifications compared to the previous structure. However, it was necessary to find a way to decrease one higher-order resonance of the main resonator located above the 5 GHz WLAN frequencies. This goal was obtained by looking at the surfaces current of each resonant mode of the patch and adding a new slot in this main resonator at a position that increases the current path of this mode without modifying the first and the third ones (slot 2 in Fig. 1). Adding a slot in this area creates a capacitive effect, which has a strong influence on this mode because the facing metal surfaces are not at the same potential, and less effect on the lower modes because, at these frequencies, these surfaces are almost at the same potential.

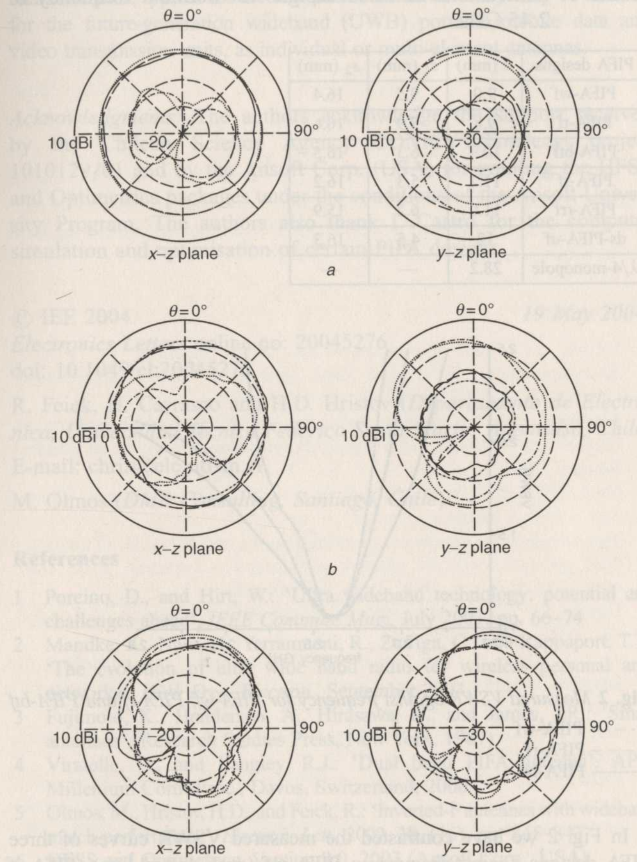

Fig. 3 *Measured and simulated radiation gain patterns of multiband antenna*

Antenna orientation given in Fig. 1
a 910 MHz *b* 1850 MHz *c* 5350 MHz
· · · · · · E_{theta}, measured ——— E_{phi}, measured
– · – · – E_{theta}, simulated ---------- E_{phi}, simulated

Results: Fig. 2 shows the measured and simulated VSWRs of the antenna. Taking into account the complexity of the structure and the resulting manufacturing tolerance errors, reasonable agreement is observed between these curves. The measured bandwidths with a VSWR better than 2.5:1 are 70 MHz (870–940 MHz) in the GSM band, 476 MHz (1608–2084 MHz) in the DCS/PCS/UMTS band and 1128 MHz (4863–5991 MHz) in the 5 GHz WLAN band. The upper standard is obtained thanks to the use of the tuned frequencies of a higher-order mode of the main patch at 5.3 GHz and the seventh mode of parasitic element 1 at 5.9 GHz. The measured and simulated radiation patterns of the antenna are depicted in Fig. 3. Due to the dipole-like behaviour coming from the antenna–PCB combination, the 910 MHz radiation pattern in the *x–z* plane is omnidirectional. Some directivity appears and increases with frequency in both planes since the length of the PCB is larger than half a wavelength at 1850 MHz and about two wavelengths at 5350 MHz. The measured maximum gains are 1.2 dBi at 910 MHz, 3.9 dBi at 1850 MHz and 6.8 dBi at 5350 MHz while the simulated values are 1.4, 3.6 and 5.5 dBi, respectively. The discrepancies between theoretical and experimental results principally come from our measurement setup and especially the difficulty to correctly choke the feed cable of such antennas. The simulated total efficiency of the structure, taking into account reflection losses as well as ohmic losses, was computed to be above 63.4, 80.7 and 83.4% in the GSM, DCS/PCS/UMTS and 5 GHz WLAN bands, respectively. Using a Wheeler Cap technique, the efficiencies were measured to be above 61 and 78% in the two lower bands, but it was impossible to measure it around 5 GHz as the antenna is now larger than the Wheeler radiansphere $\lambda/2\pi$.

Conclusions: A novel miniature multiband antenna suitable for mobile phone and WLAN applications has been presented. To our knowledge, this is the first internal handset antenna radiating in the GSM, DCS, PCS, UMTS and 5 GHz WLAN bands with a VSWR better than 2.5 and good efficiency.

Acknowledgment: This work was supported by France Telecom R&D, under contract No. 424 76-344.

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References

1 Guo, Y.-X., Chia, M.Y.W., and Chen, Z.N.: 'Miniature built-in quad band antennas for mobile handsets', *IEEE Antennas Wirel. Propag. Lett.*, 2003, **2**, pp. 30–32
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PIFA input bandwidth enhancement by changing feed plate silhouette

R. Feick, H. Carrasco, M. Olmos and H.D. Hristov

2.45 GHz planar inverted-F antenna (PIFA) designs mounted on a 100 mm square ground plane are examined with regard to the feed-element shape influence on the input bandwidth (BW). While the traditional wire-fed PIFA has a BW from about 4 to 12%, the novel PIFAs with diverse feed plates (triangular, bi-triangular, rectangular, rounded-rectangular and U-strip) are designs capable of a much broader BW, between 18 and 25% for some configurations.

Introduction: The current PCS and mobile antennas are specified for a rather narrow input bandwidth, normally less than 7–10%. Some future broadband and ultra-wideband (UWB) communication technologies, however, are very challenging with regard to antenna bandwidth. The Federal Communications Commission has recently approved the use of UWB transmission systems, defined as any device with a fractional bandwidth in excess of 20% or having a bandwidth greater than 500 MHz with a carrier frequency in the range 3.1–10.6 GHz [1, 2]. This underlines the growing need for broadband antennas. The fact that UWB devices will be short-range, small-size systems requires the design of commensurately compact antennas.

The planar inverted-F antenna (PIFA) has become one of the most usable antennas in portable wireless units [3]. It is a low-profile design,

Attachment B-2

Compact internal multiband antenna for mobile phone and WLAN standards

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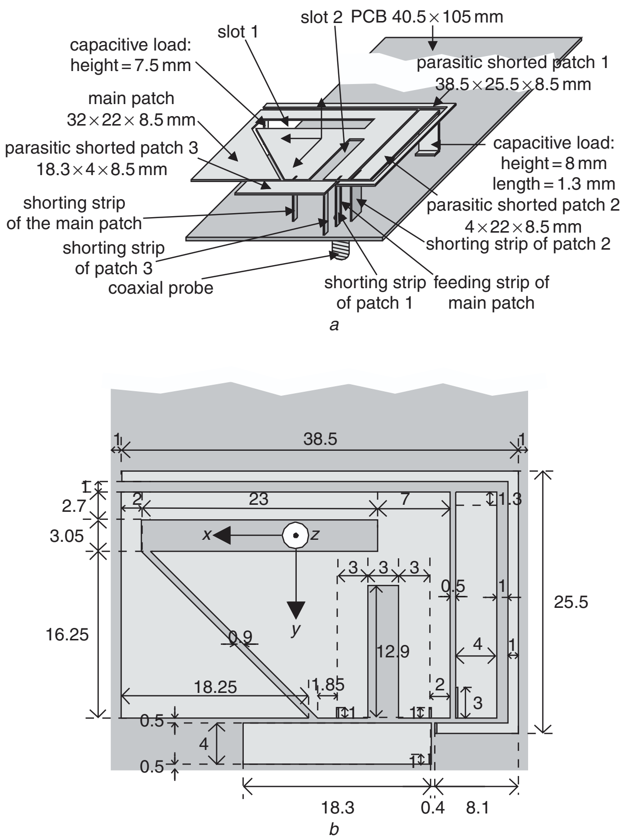

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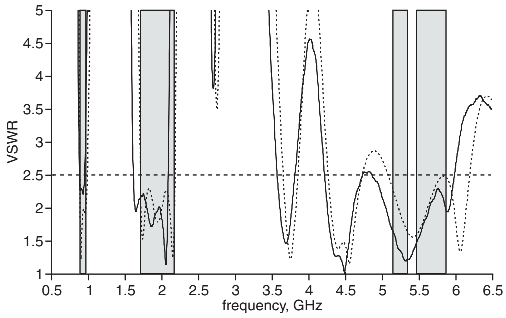

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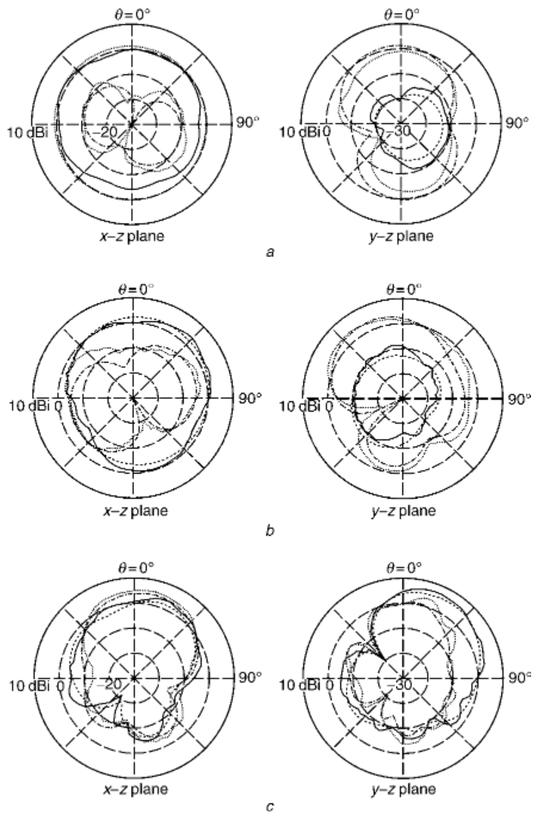
Standards bandwidth requirement in grey
—— measurement ------ simulation



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Attachment C-1

Compact Planar Monopole Antenna for Multi-band Mobile Phones

Xu Jing, Zhengwei Du and Ke Gong
State Key Lab on Microwave and Digital Communications
Department of Electronic Engineering
Tsinghua University, Beijing, People's Republic of China
E-mail: jingxu99@mails.tsinghua.edu.cn

***Abstract* - A novel planar monopole antenna suitable for mobile handset applications is presented in this paper. The antenna is mainly composed of a rectangular radiating patch with a meandered slot on, and due to the slot three branches are constructed, two resonating branches and a tuning one. The antenna is printed on a FR4 substrate and fed by a 50Ω microstrip line. A prototype has been fabricated and studied. The resulting antenna is able to operate in the GSM, DCS, PCS, UMTS and WLAN bands with a voltage standing wave radio (VSWR) better than 2.5. Both simulated and measured results are presented.**

I. Introduction

The rapid development of modern wireless communication systems has caused wide interests in designing wide-band and multi-band antennas. A variety of antenna configurations have been reported to be promising candidates for mobile handsets, such as the planar inverted-F antenna (PIFA)[1]-[3], the planar wire antenna[4], and the planar monopole antenna[5]-[8]. PIFA usually has a compact size, but its bandwidth is relatively narrow and a sufficient height from the ground plane has to be kept to achieve the acceptable performances. The planar wire antenna exhibits a much wider bandwidth, but its large size and external configuration make it less practicable in mobile applications. The planar monopole antennas proposed in [5]-[8] generally possess compact size, sufficient bandwidth and satisfying radiation patterns. However, their structures are all 3-dimensional instead of 2-dimensional, increasing the manufacture difficulty and cost.

In this paper, a novel planar monopole antenna with a 2-dimensional structure is introduced. Both the structure and the parameters are carefully adjusted to achieve multi-resonances, sufficient bandwidths and convenient profile. Printed on a dielectric board, the antenna consists of three branches. At first, two branches are designed to resonate at certain frequencies, and then another one is added for fine tuning. With a small area of 36×15 mm^2, the antenna meets the demand of the following communication standards: GSM (Global System for Mobile communications, 890-960 MHz), DCS (Digital Communication System, 1710-1880 MHz), PCS

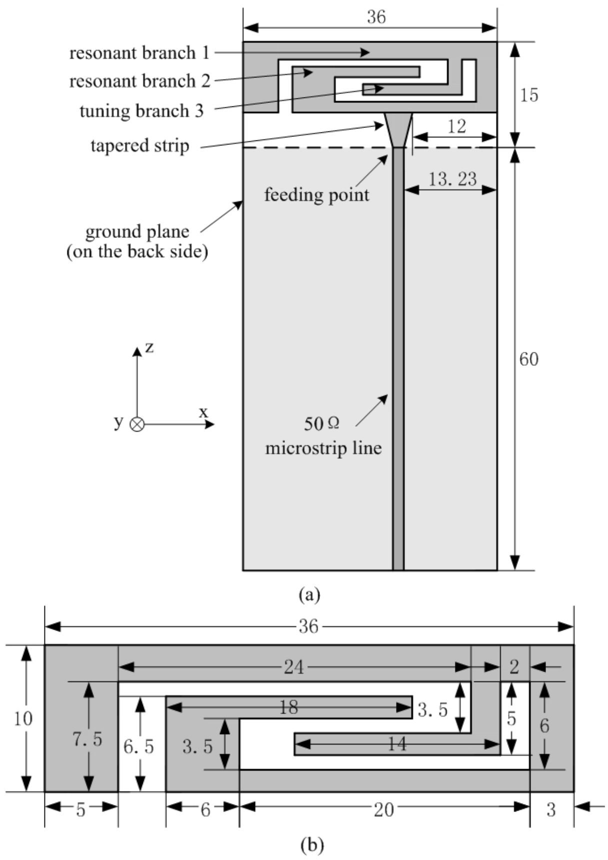

Fig. 1. Configuration of the proposed planar monopole antenna. (a) General view of the antenna. (b) Detailed dimensions of the main radiating element. All dimensions are in millimeter.

(Personal Communication Services, 1850-1990 MHz), UMTS (Universal Mobile Telecommunications System, 1920-2170 MHz), and WLAN (Wireless Local Area Network, 2400-2484 MHz). Details of the design are described in the second section, and measured results of the prototype in the third.

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II. Antenna Design

The general view of the proposed antenna is shown in Fig. 1(a), and details of the design dimensions in Fig. 1(b). The planar monopole occupies an area of 36×15 mm^2, and is printed on a 0.8-mm FR4 substrate (relative permittivity 4.4). The substrate, 36 mm in width and 75 mm in length, is considered to be the typical system circuit board of a mobile phone. On the back surface of the substrate, a ground plane of 36 mm in width and 60 mm in length is printed and treated as the system ground plane. The monopole is fed by a 50Ω microstrip line, as shown in Fig. 1(a).

The main radiating element is in the shape of a rectangle. With a meandered slot on the patch, three branches are constructed, which are designated as resonant branch 1 (the longer branch), resonant branch 2 (the shorter branch) and tuning branch 3 (the additional inner branch) respectively in Fig. 1. Between the rectangular patch and the feeding microstrip line, a tapered strip of 5-mm length is printed. The width of the strip changes linearly from 1.54 mm at the feeding point to 4 mm at the edge of the patch, improving the impedance matching at the feeding point.

At the beginning of the design, only the two resonant branches 1 and 2 are taken into account, which present two surface current paths of different lengths. The length of the longer path, calculated from the feeding point to the open end of resonant branch 1, is selected to be about 75 mm. This value is very close to one-quarter wavelength of 900-MHz frequency in free space. It is instructive to note that the resonating frequency is affected by both the length of the path and the width of the open end. In the same way, the length of the shorter path, from the feeding point to the open end of resonant branch 2, is found to be about 35 mm, approximately one-quarter wavelength of 2-GHz frequency. The slight difference is mainly because of the existence of the substrate, which shortens the resonating wavelength.

The antenna with only the two resonant branches 1 and 2 is capable of dual-band operation. However, the bandwidth is not sufficient to cover all the five bands listed above, especially the WLAN band. Thus, the tuning branch 3 is added at a proper position on resonant branch 1. Simulation results have shown that by carefully adjusting the dimensions of branch 3, the fundamental and higher modes of branch 1 can be tuned to appropriate frequencies. According to the simulation data, the resonant frequency of the fundamental mode is reduced from 960 MHz to 910 MHz. As for the higher mode, the resonant frequency is changed from higher than 3 GHz to about 2.5GHz. Thus, the antenna with all the three branches is suitable for GSM/DCS/PCS/UMTS/WLAN operation. The simulated return loss of the antennas with and without tuning branch 3 is presented in Fig. 2 for reference. The results are gained through Ansoft HFSS (High Frequency Structure Simulator) software.

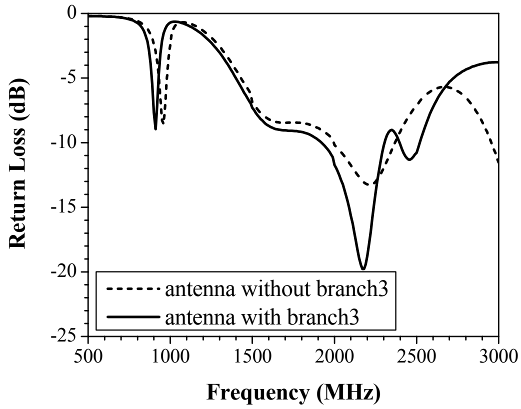

Fig. 2. Simulated return loss of the antennas with and without tuning branch 3.

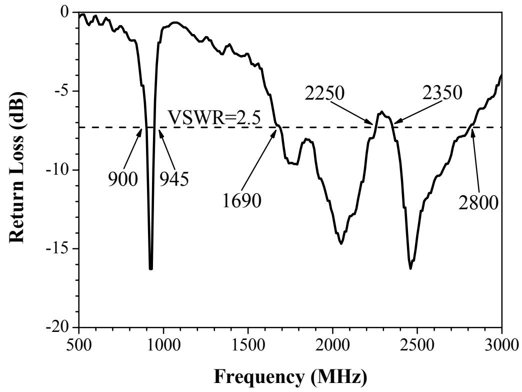

Fig. 3. Measured return loss of the proposed antenna.

III. Measured Results

A prototype was constructed according to the design dimensions, and the measured return loss is shown in Fig. 3. Three resonating modes at 920, 2050 and 2460 MHz can be clearly observed. The first impedance bandwidth at 920 MHz is 45 MHz (900-945 MHz) with the VSWR (voltage standing wave ratio) better than 2.5. The second bandwidth at 2050 MHz is 560MHz (1690-2250 MHz), covering the DCS (1710-1880 MHz), PCS (1850-1990 MHz) and UMTS (1920-2170 MHz) bands. The third bandwidth at 2460 MHz is 450 MHz (2350-2800 MHz), covering the WLAN (2400-2484 MHz) band. However, it is observed that the bandwidth of the lowest resonating mode is insufficient to cover the GSM (890-960 MHz) band. More work has to be done to enhance the bandwidth, concentrating on the dimensions of resonant branch 1, the position of the feeding point, and the effects of parasitic elements.

Besides the return loss, the radiation characteristics of the proposed antenna are also studied. The measured radiation patterns in the x-y plane and y-z plane at 920 MHz, 1800 MHz, 2000 MHz and 2400 MHz are depicted in Fig.4. A lack

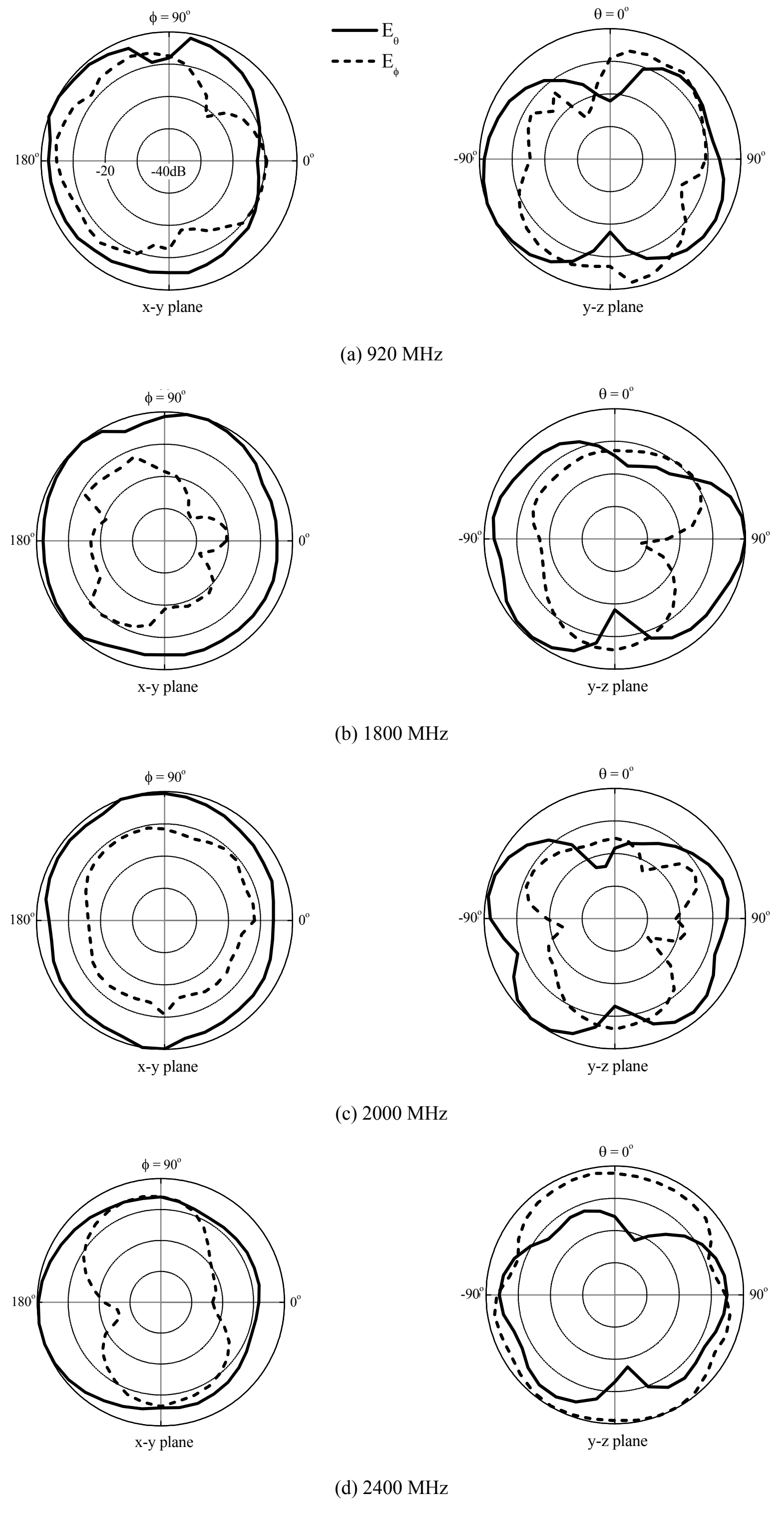

Fig. 4. Measured radiation patterns of the proposed antenna at (a) 920 MHz, (b) 1800 MHz, (c) 2000 MHz and (d) 2400 MHz.

of polarization purity is observed in the figure. As a matter of fact, this is not a drawback since the urban communication environments are so complicated that both vertical and horizontal polarization may exist [9].

IV. Conclusions

A compact multi-band planar monopole antenna capable of mobile handset applications is proposed in the paper. A prototype is constructed based on the design. Occupying a small area of 36×15 mm^2, the antenna meets the demand of GSM/DCS/PCS/UMTS/WLAN multi-band operation. Good radiation characteristics have been observed. The bandwidth for GSM band is still 25 MHz insufficient, more bandwidth-enhancement work being expected.

Acknowledgment

This work has been supported by the National Natural Science Foundation of China under Grants 60271007 and the Chinese National High-Tech program (863-2003AA123110). The authors appreciate the help in antenna measurement from G. Yan and F. Wang, Department of Electronic Engineering, Tsinghua University.

References

[1] Pey-Ling Teng, Shyh-Tirng Fang, and Kin-Lu Wong, "PIFA with a bent, meandered radiating arm for GSM/DCS dual-band operation". *Antennas and Propagation Society Int. Symp.*, Vol.3, pp.107-110, Jun. 2003.
[2] Shih-Huang Yeh, Kin-Lu Wong, Tzung-Wern Chiou, and Shyh-Tirng Fang, "Dual-band planar inverted F antenna for GSM/DCS mobile phones". *IEEE Trans. Antennas Propagat.*, Vol.51, pp.1124-1126, May. 2003.
[3] P. Ciais, R. Staraj, G. Kossiavas, and C. Luxey, "Compact internal multiband antenna for mobile phone and WLAN standards". *Electron. Lett.*, Vol.40, Jul. 2004.
[4] R. L. Li, G. DeJean, M. M. Tentzeris, and J. Laskar, "Novel multi-band broadband planar wire antennas for wireless communication handheld terminals". *Antennas and Propagation Society Int. Symp.*, Vol.3, pp.44-47, Jun. 2003.
[5] Ching-Yuan Chiu, Pey-Ling Teng and Kin-Lu Wong, "Shorted, folded planar monopole antenna for dual-band mobile phone". *Electron. Lett.*, Vol.39, Sep. 2003.
[6] Pey-Ling Teng, Hong-Twu Chen, and Kin-Lu Wong, "Multi-frequency planar monopole antenna for GSM/DCS/PCS/WLAN operation". *Microwave Opt. Technol. Lett.*, Vol.36, pp.350-352, Mar. 2003.
[7] Pey-Ling Teng and Kin-Lu Wong, "Planar monopole folded into a compact structure for very-low-profile multiband mobile-phone antenna". *Microwave Opt. Technol. Lett.*, Vol.33, pp.22-25, Apr. 2002.
[8] I. F. Chen and C. M. Chiang, "Multi-folded tapered monopole antenna for wideband mobile handset applications". *Electron. Lett.*, Vol.40, May. 2004.
[9] P. Ciais, R. Staraj, G. Kossiavas, and C. Luxey, "Design of an internal quad-band antenna for mobile phones". *IEEE Microwave Wireless Comp. Lett.*, Vol.14, pp.148-150, Apr. 2004.

Attachment C-2

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Compact planar monopole antenna for multi-band mobile phones

Publisher: IEEE Cite This PDF

Xu Jing ; Zhengwei Du ; Ke Gong All Authors

Abstract:
A novel planar monopole antenna suitable for mobile handset applications is presented in this paper. The antenna is mainly composed of a rectangular radiating patch with a meandered slot on, and due to the slot three branches are constructed, two resonating branches and a tuning one. The antenna is printed on an FR4 substrate and fed by a 50/spl Omega/ microstrip line. A prototype has been fabricated and studied. The resulting antenna is able to operate in the GSM, DCS, PCS, UMTS and WLAN bands with a voltage standing wave ratio (VSWR) better than 2.5. Both simulated and measured results are presented.

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SECTION I.
Introduction

The rapid development of modern wireless communication systems has caused wide interests in designing wide-band and multi-band antennas. A variety of antenna configurations have been reported to be promising candidates for mobile handsets, such as the planar inverted-F antenna (PIFA) [1]– [3], the planar wire antenna [4], and the planar monopole antenna [5]– [8]. PIFA usually has a compact size, but its bandwidth is relatively narrow and a sufficient height from the ground plane has to be kept to achieve the acceptable performances. The planar wire antenna exhibits a much wider bandwidth, but its large size and external configuration make it less practicable in mobile applications. The planar monopole antennas proposed in [5]– [8] generally possess compact size, sufficient bandwidth and satisfying radiation patterns. However, their structures are all 3-dimensional instead of 2-dimensional, increasing the manufacture difficulty and cost.

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The general view of the proposed antenna is shown in Fig. 1(a), and details of the design dimensions in Fig. 1(b). The planar monopole occupies an area of $36 \times 15\ \mathrm{mm}^2$:, and is printed on a 0.8-mm FR4 substrate (relative permittivity 4.4). The substrate, 36 mm in width and 75 mm in length, is considered to be the typical system circuit board of a mobile phone. On the back surface of the substrate, a ground plane of 36 mm in width and 60 mm in length is printed and treated as the system ground plane. The monopole is fed by a 50Ω microstrip line, as shown in Fig. 1(a).

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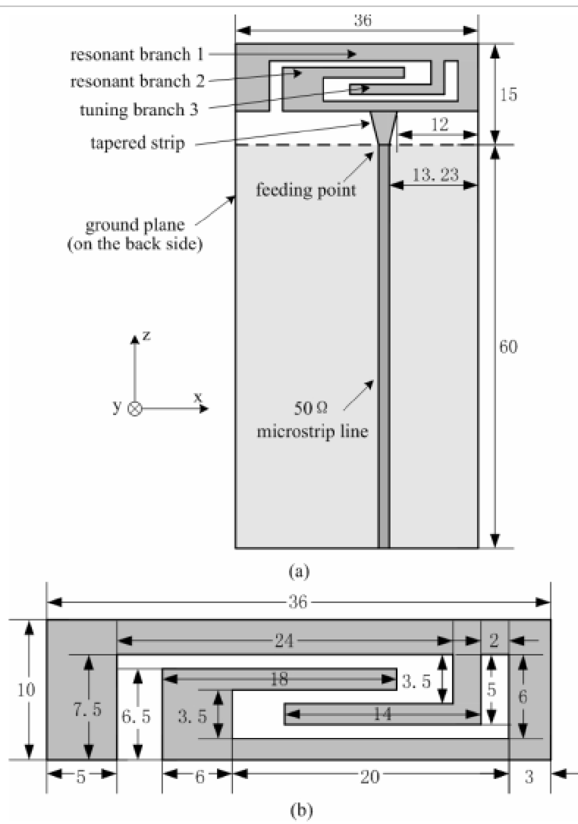

Fig. 1. Configuration of the proposed planar monopole antenna. (a) General view of the antenna. (b) Detailed dimensions of the main radiating element. All dimensions are in millimeter.

At the beginning of the design, only the two resonant branches 1 and 2 are taken into account, which present two surface current paths of different lengths. The length of the longer path, calculated from the feeding point to the open end of resonant branch 1, is selected to be about 75 mm. This value is very close to one-quarter wavelength of 900-MHz frequency in free space. It is instructive to note that the resonating frequency is affected by both the length of the path and the width of the open end. In the same way, the length of the shorter path, from the feeding point to the open end of resonant branch 2, is found to be about 35 mm, approximately one-quarter wavelength of 2-GHz frequency. The slight difference is mainly because of the existence of the substrate, which shortens the resonating wavelength.

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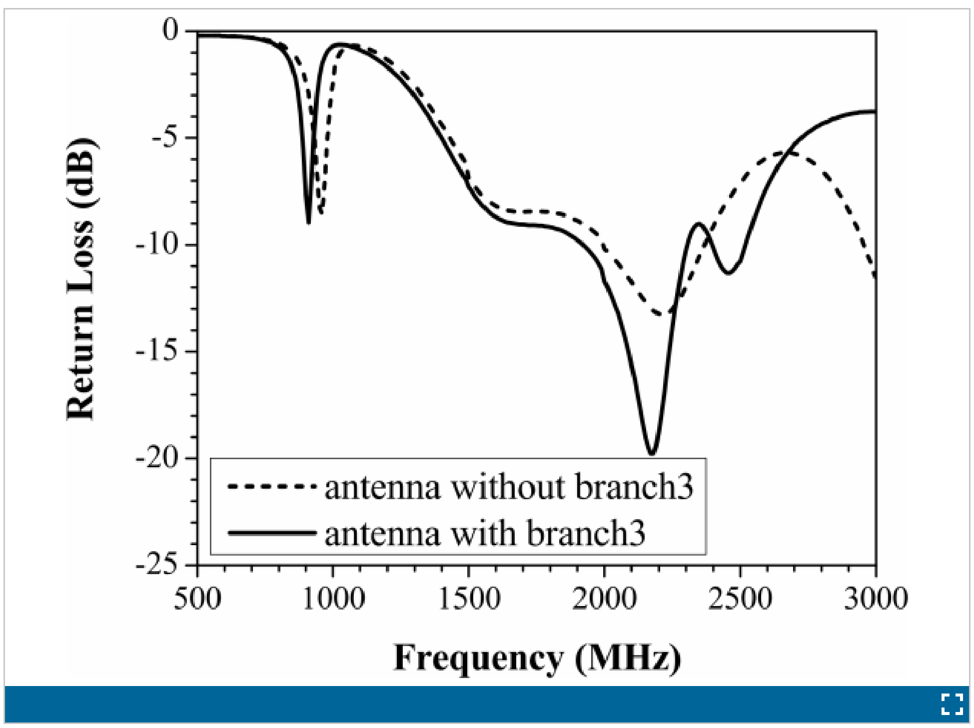

Fig. 2. Simulated return loss of the antennas with and without tuning branch 3.

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SECTION III.
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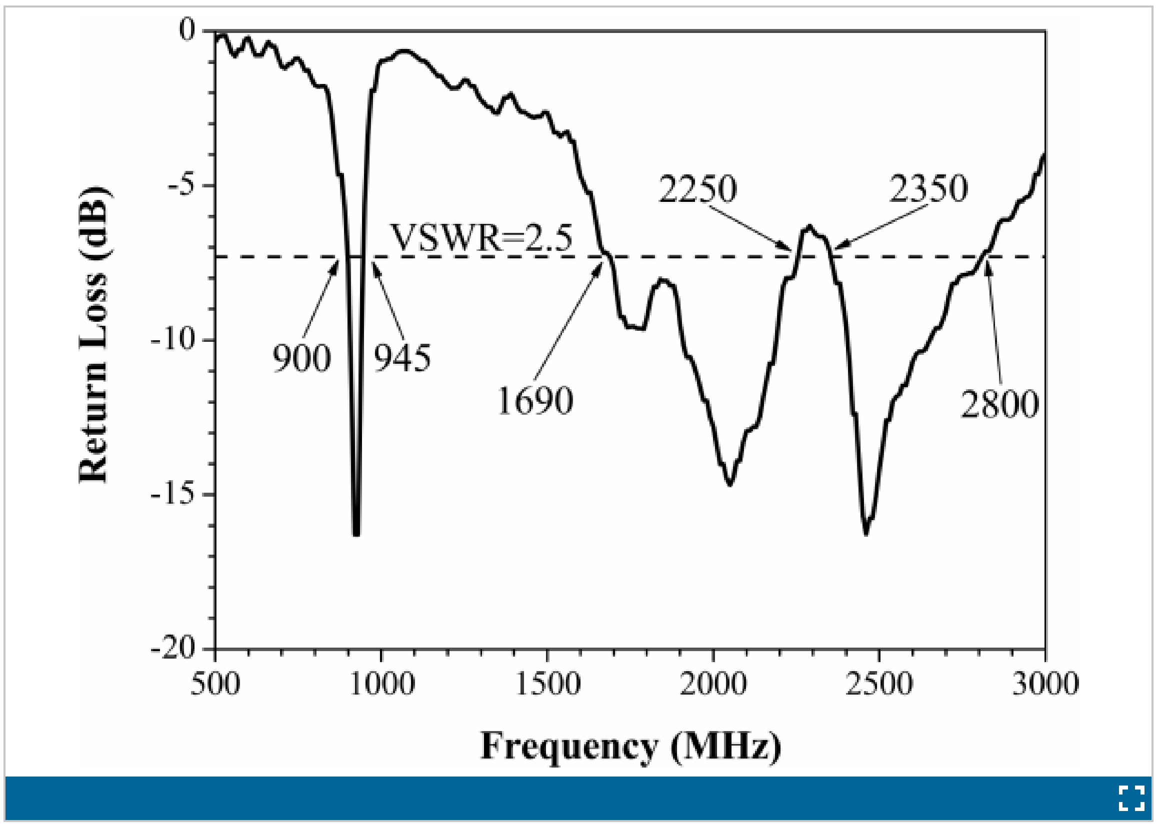

Fig. 3. Measured return loss of the proposed antenna.

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Besides the return loss, the radiation characteristics of the proposed antenna are also studied. The measured radiation patterns in the x-y plane and y-z plane at 920 MHz, 1800 MHz, 2000 MHz and 2400 MHz are depicted in Fig. 4. A lack of polarization purity is observed in the figure. As a matter of fact, this is not a drawback since the urban communication environments are so complicated that both vertical and horizontal polarization may exist [9].

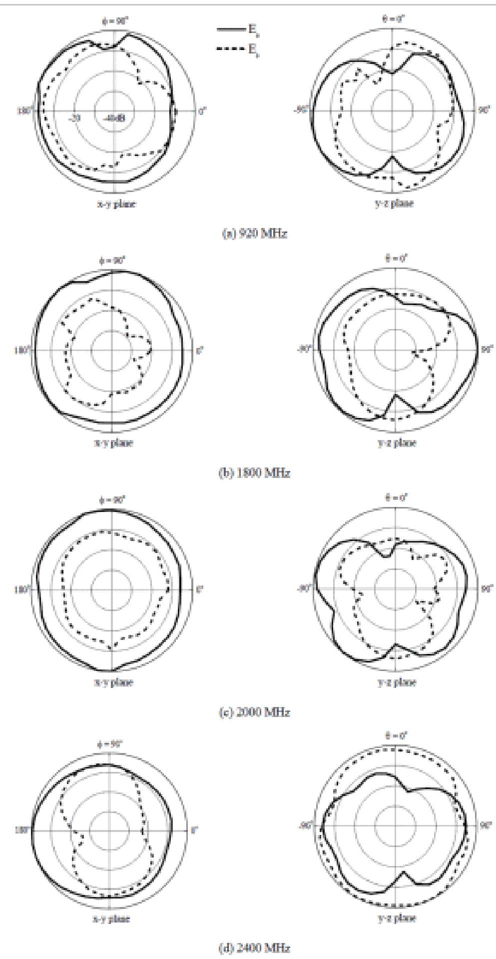

Fig. 4. Measured radiation patterns of the proposed antenna at (a) 920 MHz, (b) 1800 MHz, (c) 2000 MHz and (d) 2400 MHz.

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SECTION IV.
Conclusions

A compact multi-band planar monopole antenna capable of mobile handset applications is proposed in the paper. A prototype is constructed based on the design. Occupying a small area of $36 \times 15\ \mathrm{mm}^2$ the antenna meets the demand of GSM/DCS/PCSIUMTS/WLAN multi-band operation. Good radiation characteristics have been observed. The bandwidth for GSM band is still 25 MHz insufficient, more bandwidth-enhancement work being expected.

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PART I OF TWO PARTS

SPECIAL ISSUE ON ANTENNAS AND PROPAGATION APPLICATIONS

(Contents Continued on Page 2361)

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(Contents Continued from Front Cover)

An Inverted FL Antenna for Dual-Frequency Operation

Hisamatsu Nakano, *Fellow, IEEE*, Yusuke Sato, Hiroaki Mimaki, *Member, IEEE*, and Junji Yamauchi, *Member, IEEE*

***Abstract*—An inverted FL antenna (InvFLA) is analyzed to obtain dual-frequency operation at 2.45 and 5.2 GHz (wireless LAN system frequencies). The InvFLA is composed of inverted FL elements, a parasitic element, and a ground plate, where these lie in the same plane, i.e., the structure is a card-type structure having a co-planar ground plate. The antenna height above the ground plate is very small: $5.5\ \mathrm{mm} = 0.045$ wavelength at 2.45 GHz. The analysis shows that the InvFLA has a 4.1% bandwidth around 2.45 GHz and a 31.8% bandwidth around 5.2 GHz, both for a $\mathrm{VSWR} = 2$ criterion. The gain is calculated to be 0.9 dBi at 2.45 GHz and 1.7 dBi at 5.2 GHz, with a small gain variation in each of the VSWR bands.**

***Index Terms*—Card-type antenna, dual-frequency operation, finite-difference time-domain (FDTD) analysis, inverted F, inverted L.**

I. Introduction

The increasing demand for wireless communications has been accelerating development of new antennas that operate in the required frequency bands [1]–[5]. The dual-frequency antenna is one of these new antennas, and so far numerous efforts have been made in this area [6]–[8]. For example, Wong has investigated microstrip patches for dual-frequency operation and summarized them in [9].

This paper presents an antenna that responds to the above-mentioned trend: an inverted FL antenna (InvFLA) for dual-frequency operation. The InvFLA is made of a thin conducting film, having a flat structure, as shown in Fig. 1(b), where both the radiation element (inverted F and L strip lines) in the positive y space and the ground plate (GP) in the negative y space lie in the same plane (x-y plane). In other words, the InvFLA has a co-planar ground plate, forming a card-type antenna structure.

The card-type InvFLA structure differs from the layered microstrip antenna structure for dual-frequency operation in [9], where the ground plate backs a radiation element (patch element), i.e., the patch is parallel to the ground plate. It is emphasized that the card-type structure facilitates the use of the InvFLA in PC card devices for personal computers or inside mobile phone handsets.

After a brief summary of the analysis methods, which are based on the finite-difference time-domain method (FDTDM) [10], this paper investigates an InvFLA for realizing dual-frequency operation at 2.45 and 5.2 GHz (frequencies used for wireless LAN communications). Note that the final structural parameters for the InvFLA are obtained through a step-by-step investigation of the following structures: 1) an inverted L element; 2) an inverted F element; 3) a compound of the inverted L and F elements, referred to as a *compounded LF*; 4) the compounded LF with a parasitic inverted L element; and 5) the compounded LF with a *modified* parasitic inverted L element. Also, note that the design process presented in this paper is not necessarily restricted to the specific frequencies 2.45 and 5.2 GHz. It is possible to apply the same design technique to other dual-frequency antenna designs.

For confirmation of the FDTDM results (obtained using the FDTDM computer programs developed by the authors), experimental results are presented. A good agreement between the FDTDM results and the experimental results is found.

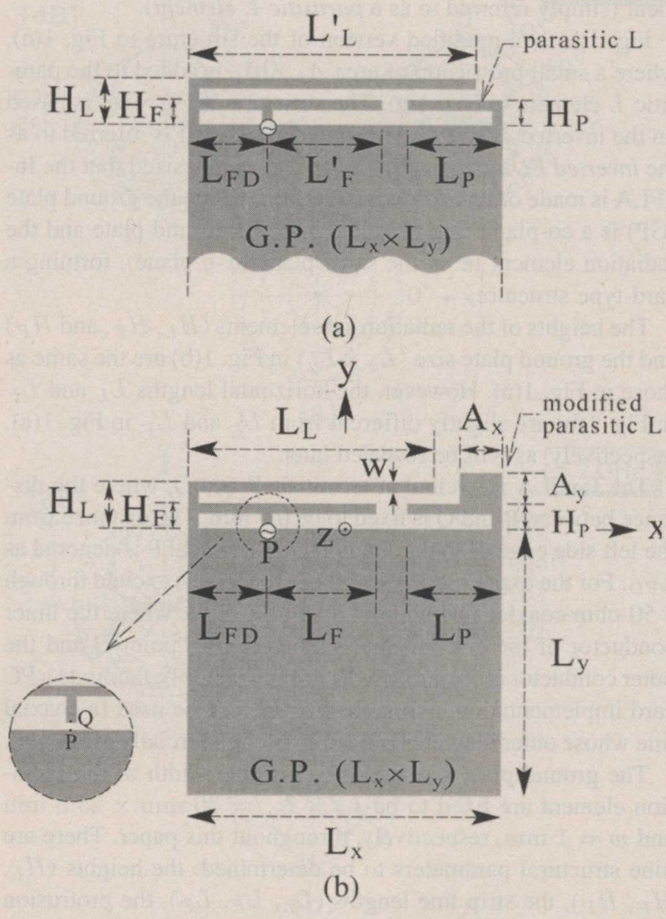

Fig. 1. Antenna structures. (a) A compound of inverted L and F elements (referred to as a *compounded LF*) with a parasitic L element above a co-planar ground plate (GP). (b) A compounded LF with a modified parasitic L element above a co-planar ground plate, referred to as the inverted FL antenna (InvFLA). The ground plate size in (a) is the same as that in (b): $L_x \times L_y = 30\ \mathrm{mm} \times 25.5\ \mathrm{mm}$.

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II. Configuration

Fig. 1(a) shows a step involved in reaching the antenna structure of Fig. 1(b). The radiation element in Fig. 1(a) is a compound of three sub-elements: an inverted L element (see inset (I) of Fig. 2, where elements α-β-γ and α'-β'-γ' are collectively referred to as the "inverted L element"), an inverted F element (see inset (II) of Fig. 2), and a parasitic inverted L element (simply referred to as a *parasitic* L *element*).

Fig. 1(b) is a modified version of the structure in Fig. 1(a), where a small protrusion of area $A_x \times A_y$ is added to the parasitic L element in Fig. 1(a). The structure of Fig. 1(b) is based on the inverted L and F elements, and hence it is referred to as the *inverted FL antenna* (InvFLA). It is emphasized that the InvFLA is made of a thin conducting film, where the ground plate (GP) is a co-planar ground plate, i.e., the ground plate and the radiation element lie in the same plane (x-y plane), forming a card-type structure.

The heights of the radiation sub-elements (H_L, H_F, and H_P) and the ground plate size ($L_x \times L_y$) in Fig. 1(b) are the same as those in Fig. 1(a). However, the horizontal lengths L_L and L_F in Fig. 1(b) are slightly different from L'_L and L'_F in Fig. 1(a), respectively, as will be revealed later.

The InvFLA is excited at terminals P and Q, where the distance between P and Q is fixed to be 0.5 mm. The distance from the left side edge of the ground plate to terminal P is denoted as $L_{\rm FD}$. For the experimental work, the InvFLA is excited through a 50-ohm coaxial line without a balun circuit, where the inner conductor of the coaxial line is connected to point Q and the outer conductor is soldered to the ground plate. To facilitate a PC card implementation, a thin coaxial line can be used (a coaxial line whose outer diameter is 0.8 mm is commercially available).

The ground plate size and the strip line width of the radiation element are fixed to be $L_x \times L_y = 30$ mm $\times$ 25.5 mm and $w = 1$ mm, respectively, throughout this paper. There are nine structural parameters to be determined: the heights (H_L, H_F, H_P), the strip line lengths (L_L, L_F, L_P), the protrusion size (A_x, A_y), and the feed point location $L_{\rm FD}$. In this paper, the heights (H_L, H_F, H_P) are pre-selected to be small with respect to the wavelengths at 2.45 and 5.2 GHz: $(H_L, H_F, H_P) = (4.5\ \mathrm{mm},\ 2.5\ \mathrm{mm},\ 2.5\ \mathrm{mm})$. The remaining structural parameters (L_L, L_F, L_P), (A_x, A_y) and $L_{\rm FD}$ are to be determined for operation at 2.45 and 5.2 GHz.

III. Analysis and Discussion

Analysis is performed using the finite-difference time-domain method (FDTDM). For this, Yee's algorithm based on rectangular cells [10] is adopted, where the analysis space is terminated using Liao's second order absorbing boundary condition [11]. The antenna excitation is modeled by a delta-gap voltage source $V_{\rm in}(t)$, which is defined by a sine function modulated by a Gaussian function: $V_{\rm in}(t) = V_{\rm gauss}(t) \sin \omega t$, where $V_{\rm gauss}(t) = \exp\{-(t-T)/KT\}^2$, with $K = 0.29$ and $T = 0.646/f_{\rm 3dB}$. Note that $f_{\rm 3dB}$ is the frequency at which the power spectrum ($|$Fourier transform of $V_{\rm gauss}(t)|^2$) drops 3 dB from its maximum value. The electric field at a far-field point, $E_{\rm Far}$ (composed of E_θ and E_ϕ), is calculated on the basis of the equivalence principle [12].

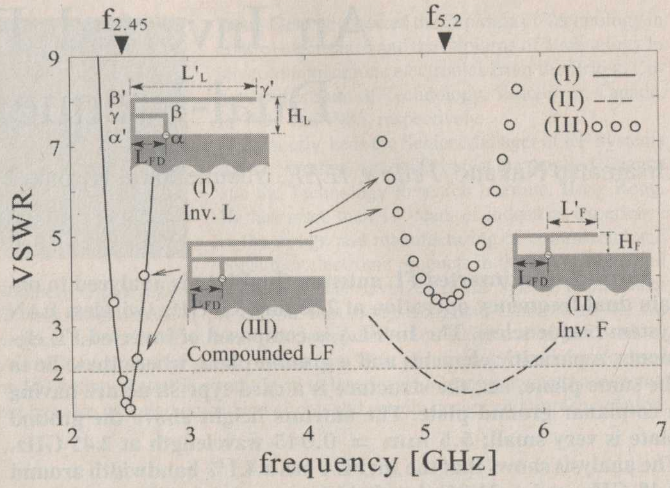

Fig. 2. VSWRs of three structures. The structural parameters for an inverted L element (I) are $(H_L,\ L'_L) = (4.5\ \mathrm{mm},\ 27.5\ \mathrm{mm})$ and $L_{\rm FD} = 7.5$ mm, and those for an inverted F element (II) are $(H_F,\ L'_F) = (2.5\ \mathrm{mm},\ 11\ \mathrm{mm})$ and $L_{\rm FD} = 7.5$ mm. A compounded LF (III) has the same structural parameters used for the sub- elements (I) and (II). The ground plate sizes in structures (I), (II), and (III) are the same: $L_x \times L_y = 30$mm $\times$ 25.5 mm.

The InvFLA is intended for installation in *mobile* equipment. In such a case, polarization purity (low cross polarization) is not required; however, an appropriate VSWR frequency response must be realized. The structural parameters for the InvFLA, Fig. 1(b), are obtained through the five steps described below, where the first three steps are rough adjustments and the fourth and fifth steps are devoted to a fine-tuning of the design.

For the first step, the inverted L element [see inset (I) of Fig. 2] is analyzed for a height of $H_L = 4.5\mathrm{mm} = 0.0368\lambda_{2.45}$, pre-selected in Section II, where $\lambda_{2.45}$ is the wavelength at 2.45 GHz ($\equiv f_{2.45}$). To obtain resonance around $f_{2.45}$, the horizontal length L'_L is chosen such that the total length $H_L + L'_L$ is close to one-quarter wavelength at $f_{2.45}$: $L'_L = 27.5$ mm ($H_L + L'_L = 32$ mm $= 0.261\lambda_{2.45}$). Resonance at $f_{2.45}$ is realized by adjusting the location of feed point (distance $L_{\rm FD}$). The VSWR frequency response for $L_{\rm FD} = 7.5$ mm is shown by the solid line in Fig. 2.

The second step is performed using the inverted F element shown in inset (II) of Fig. 2. The height H_F is chosen to be smaller than H_L for the inverted L element, described in Section II: $H_F = 2.5$ mm $= 0.0433\lambda_{5.2}$, where $\lambda_{5.2}$ is the wavelength at 5.2 GHz ($\equiv f_{5.2}$). The feed point is located at the same point as that for the aforementioned inverted L element ($L_{\rm FD} =$ 7.5 mm). Resonance around $f_{5.2}$ is obtained by choosing the horizontal length L'_F such that the $H_F + L'_F$ is close to one-quarter wavelength at $f_{5.2}$: $L'_F = 11$ mm ($H_F + L'_F =$ 13.5 mm $= 0.234\lambda_{5.2}$). The VSWR for this structure is shown by the broken line in Fig. 2. Note that the horizontal lengths L'_F (obtained in the second step) and L'_L (obtained in the first step) are slightly changed to L_F and L_L, respectively, after the fine-tuning in the fifth step.

The third step is to compound the inverted L and F elements determined in the first and second steps, as shown in inset (III) of Fig. 2. The white dots in Fig. 2 show the VSWR for this structure. It is observed that the VSWR at $f_{2.45}$ remains almost unchanged; however the VSWR at $f_{5.2}$ deteriorates due to mutual

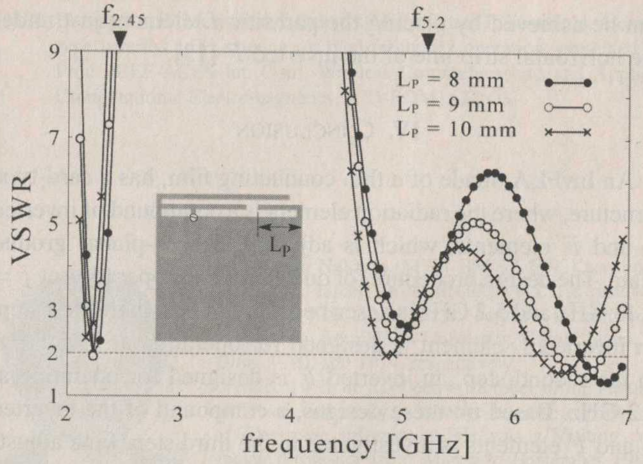

Fig. 3. Effects of the length of a parasitic L element, L_P, on the VSWR, where the structural parameters $(H_L, L'_L) = (4.5\ \text{mm},\ 27.5\ \text{mm})$, $(H_F, L'_F) = (2.5\ \text{mm},\ 11\ \text{mm})$, and $L_{\text{FD}} = 7.5$ mm are used. The ground plate size is $L_x \times L_y = 30\ \text{mm} \times 25.5\ \text{mm}$.

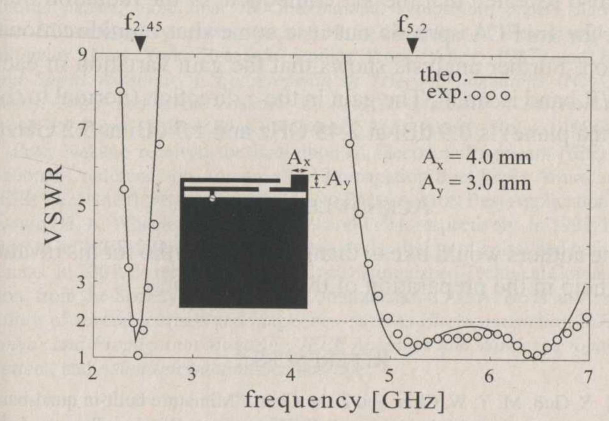

Fig. 4. VSWR for an inverted FL antenna. The structural parameters are $(H_L, L_L) = (4.5\ \text{mm},\ 24.5\ \text{mm})$, $(H_F, L_F) = (2.5\ \text{mm},\ 10.5\ \text{mm})$, $L_{\text{FD}} = 7.5$ mm, $(H_P, L_P) = (2.5\ \text{mm},\ 9.0\ \text{mm})$, $(A_x, A_y) = (4.0\ \text{mm},\ 3.0\ \text{mm})$, and $(L_x \times L_y) = (30\ \text{mm} \times 25.5\ \text{mm})$.

effects between the inverted L and F elements. This is overcome in the following fourth and fifth steps.

In the fourth step, a parasitic L element is added to the structure discussed in the third step, as shown in Fig. 1(a). The height of the parasitic L element is chosen to be equal to that of the inverted F element, as described in Section II: $H_P = H_F = 2.5$ mm. Fig. 3 shows the VSWR as a function of frequency for three values of the horizontal length of the parasitic L element, L_P, where the structural parameters for the inverted L and F elements are held at the values used in the third step: $(H_L, L'_L) = (4.5\ \text{mm},\ 27.5\ \text{mm})$, $(H_F, L'_F) = (2.5\ \text{mm},\ 11\ \text{mm})$, and $L_{\text{FD}} = 7.5$ mm. It is found that the parasitic L element generates resonances between 6 and 7 GHz. Note that the total length of the parasitic L, $H_P + L_P$, is close to one-quarter wavelength at the frequency where the minimum VSWR for each L_P appears: $H_P + L_P = 0.238\lambda_{6.8}$ at 6.8 GHz for $L_P = 8$ mm, $H_P + L_P = 0.253\lambda_{6.6}$ at 6.6 GHz for $L_P = 9$ mm, and $H_P + L_P = 0.267\lambda_{6.4}$ at 6.4 GHz for $L_P = 10$ mm, where λ_f is the wavelength at frequency f.

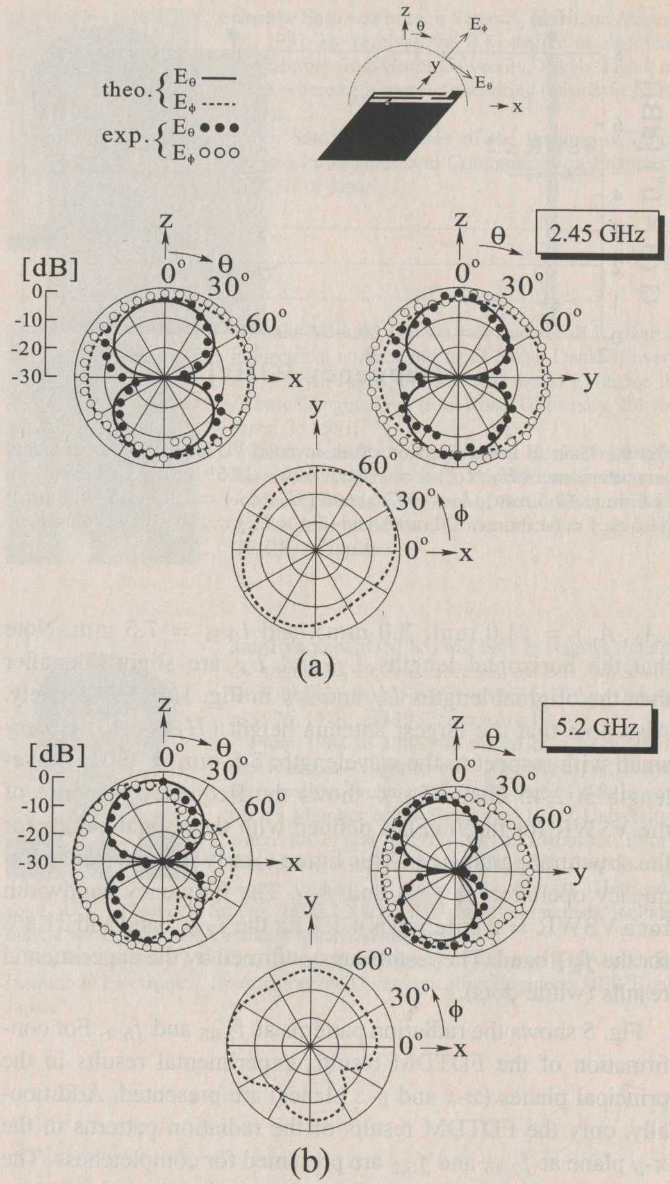

Fig. 5. Radiation patterns of an inverted FL antenna. (a) At 2.45 GHz. (b) At 5.2 GHz. The structural parameters are $(H_L, L_L) = (4.5\ \text{mm},\ 24.5\ \text{mm})$, $(H_F, L_F) = (2.5\ \text{mm},\ 10.5\ \text{mm})$, $L_{\text{FD}} = 7.5$ mm, $(H_P, L_P) = (2.5\ \text{mm},\ 9.0\ \text{mm})$, $(A_x, A_y) = (4.0\ \text{mm},\ 3.0\ \text{mm})$, and $(L_x \times L_y) = (30\ \text{mm} \times 25.5\ \text{mm})$.

At this point there are two issues: 1) the VSWR curve is slightly shifted downward with respect to frequencies $f_{2.45}$ and $f_{5.2}$; and 2) the VSWR around $f_{5.2}$ is still larger than 2. These issues are solved by the following structural modifications: 1) reduction of the original horizontal strip line lengths L'_L and L'_F, and 2) widening of the strip width of the parasitic L element. Note that the widening of the strip width is realized by making a protrusion on the parasitic L element, where part of the strip line is widened to $w + A_y$ over length A_x, as shown in Fig. 1(b).

The fifth step is to perform the aforementioned structural modifications for dual-frequency operation at 2.45 and 5.2 GHz. Using trial and error, the structural parameters are determined to be $(L_L, L_F, L_P) = (24.5\ \text{mm},\ 10.5\ \text{mm}, 9.0\ \text{mm})$,

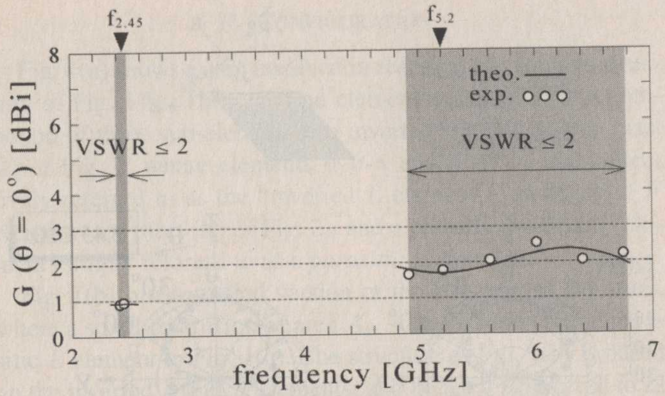

Fig. 6. Gain in the z-direction of an inverted FL antenna. The structural parameters are $(H_L, L_L) = (4.5\text{ mm}, 24.5\text{ mm})$, $(H_F, L_F) = (2.5\text{ mm}, 10.5\text{ mm})$, $L_{\rm FD} = 7.5\text{ mm}$, $(H_P, L_P) = (2.5\text{ mm}, 9.0\text{ mm})$, $(A_x, A_y) = (4.0\text{ mm}, 3.0\text{ mm})$, and $(L_x \times L_y) = (30\text{ mm} \times 25.5\text{ mm})$.

$(A_x, A_y) = (4.0\text{ mm}, 3.0\text{ mm})$, and $L_{\rm FD} = 7.5\text{ mm}$. Note that the horizontal lengths L_L and L_F are slightly smaller than the original lengths L'_L and L'_F in Fig. 1(a), respectively. Also note that the largest antenna height $(H_P + A_y)$ is very small with respect to the wavelength: $5.5\text{ mm} = 0.045$ wavelength at 2.45 GHz. Fig. 4 shows the frequency response of the VSWR for the InvFLA defined with these final values for the structural parameters. This figure clearly indicates dual-frequency operation at $f_{2.45}$ and $f_{5.2}$. The frequency bandwidth for a $\text{VSWR} = 2$ criterion is 4.1% for the $f_{2.45}$ band and 31.8% for the $f_{5.2}$ band. The results are confirmed by the experimental results (white dots).

Fig. 5 shows the radiation patterns at $f_{2.45}$ and $f_{5.2}$. For confirmation of the FDTDM results, experimental results in the principal planes (x-z and y-z planes) are presented. Additionally, only the FDTDM results of the radiation patterns in the x-y plane at $f_{2.45}$ and $f_{5.2}$ are presented for completeness. The radiation patterns are useful in understanding the gain characteristic in the z direction $G(\theta = 0°)$, which is shown in Fig. 6 together with experimental results, where the shadowed areas in the figure show the VSWR bands. It is found that the gain (with respect to an isotropic source) is approximately 0.9 dBi at $f_{2.45}$ and approximately 1.7 dBi at $f_{5.2}$, with a small gain variation in each VSWR band. These gain values are small due to the fact that the radiation is not highly directive, as seen from the radiation pattern E_ϕ.

The difference between the gains at $f_{2.45}$ and $f_{5.2}$ (i.e., the gain in the z-direction at 2.45 GHz is smaller than that at 5.2 GHz) is attributed to the following facts: 1) the radiation pattern E_ϕ at 2.45 GHz in each of the x-z and y-z planes is more omnidirectional than that at 5.2 GHz and 2) the radiation pattern E_θ at 2.45 GHz in each of the x-z and y-z planes (having a figure-eight pattern) shows a wider half-power beam width than that at 5.2 GHz.

An omnidirectional pattern is desirable for communications between a fixed base station antenna and an antenna installed in a *mobile* device. Note that, if a more omnidirectional E_ϕ pattern (in the x-z plane) is required for the InvFLA at 5.2 GHz, this can be achieved by placing the parasitic L element just under the horizontal strip line of the inverted F [13].

IV. Conclusion

An InvFLA, made of a thin conducting film, has a card-type structure, where the radiation element is a compound of inverted L and F elements, which is adjacent to a co-planar ground plate. The design procedure for dual-frequency operation at $f = 2.45$ GHz and 5.2 GHz is described in five steps. In the first step, an inverted L element is designed for operation at 2.45 GHz. In the second step, an inverted F is designed for operation at 5.2 GHz. Based on these designs, a compound of the inverted L and F elements is investigated in the third step. Fine adjustment for dual-frequency operation is performed by introducing a parasitic L element in the fourth step and then modifying the parasitic L element in the fifth step.

It is found that the VSWR frequency bandwidth of the InvFLA is 4.1% around 2.45 GHz and 31.8% around 5.2 GHz. It is also revealed that the E_ϕ component of the radiation field from the InvFLA spreads out in a somewhat omnidirectional fashion. Further analysis shows that the gain variation in each VSWR band is small. The gain in the z direction (normal to the antenna plane) is 0.9 dBi at 2.45 GHz and 1.7 dBi at 5.2 GHz.

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References

[1] Y. Guo, M. Y. W. Chia, and Z. N. Chen, "Miniature built-in quad-band antennas for mobile handsets," *IEEE Antennas Wireless Propag. Lett.*, vol. 2, pp. 30–32, 2003.

[2] M. Ali, G. J. Hayes, H. Hwang, and R. A. Sadler, "Design of multiband internal antenna for third generation mobile phone handsets," *IEEE Trans. Antennas Propag.*, vol. 51, no. 7, pp. 1452–1461, Jul. 2003.

[3] Y. Guo, I. Ang, and M. Y. W. Chia, "Compact internal multiband antennas for mobile handsets," *IEEE Antennas Wireless Propag. Lett.*, vol. 2, pp. 143–146, 2003.

[4] M. F. Abedin and M. Ali, "Modifying the ground plane and its effect on planar inverted-F antennas (PIFA's) for mobile phone handsets," *IEEE Antennas Wireless Propag. Lett.*, vol. 2, pp. 226–229, 2003.

[5] Y. Kwon, J. Moon, and S. Park, "An internal triple-band planar inverted-F antenna," *IEEE Antennas Wireless Propag. Lett.*, vol. 2, pp. 341–344, 2003.

[6] D. Llorens, P. Otero, and C. C-Penalosa, "Dual-band, single CPW port, planar-slot antenna," *IEEE Trans. Antennas Propag.*, vol. 51, no. 1, pp. 137–139, Jan. 2003.

[7] S. Yeh, K. Wong, T. Chiou, and S. Fang, "Dual-band planar inverted F antenna for GSM/DCS mobile phones," *IEEE Trans. Antennas Propag.*, vol. 51, no. 5, pp. 1124–1126, May 2003.

[8] H. Chen, W. Chen, Y. Cheng, and Y. Lin, "Dualband meander monopole antenna," in *Proc. IEEE Antennas and Propagation Soc. Int. Symp.*, vol. 3, Columbus, OH, Jun. 2003, pp. 48–51.

[9] K. Wong, *Compact and Broadband Microstrip Antennas*. New York: Wiley, 2002.

[10] A. Taflove, *Computational Electrodynamics: The Finite-Difference Time Domain Method*. Norwood, MA: Artech House, 1995.

[11] Z. P. Liao, H. L. Wong, B. P. Yang, and Y. F. Yuan, "A transmitting boundary for transient wave analysis," *Science Sinica, Series A*, vol. 27, no. 10, pp. 1063–1076, 1984.

[12] C. A. Balanis, *Antenna Theory: Analysis and Design*, 2nd ed: Wiley, 1982, pp. 575–594.

[13] H. Nakano, K. Morishita, Y. Sato, H. Mimaki, and J. Yamauchi. A card-type inverted LFL antenna for dual-frequency operation. presented at Proc. IEEE-ACES Int. Conf. Wireless Communications and Applied Computational Electromagnetics. [CD-ROM] s27p03i

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Attachment D-2

An Inverted FL Antenna for Dual-Frequency Operation

Hisamatsu Nakano, *Fellow, IEEE*, Yusuke Sato, Hiroaki Mimaki, *Member, IEEE*, and Junji Yamauchi, *Member, IEEE*

***Abstract*—An inverted FL antenna (InvFLA) is analyzed to obtain dual-frequency operation at 2.45 and 5.2 GHz (wireless LAN system frequencies). The InvFLA is composed of inverted FL elements, a parasitic element, and a ground plate, where these lie in the same plane, i.e., the structure is a card-type structure having a co-planar ground plate. The antenna height above the ground plate is very small: $5.5\ \mathrm{mm} = 0.045$ wavelength at 2.45 GHz. The analysis shows that the InvFLA has a 4.1% bandwidth around 2.45 GHz and a 31.8% bandwidth around 5.2 GHz, both for a $\mathrm{VSWR} = 2$ criterion. The gain is calculated to be 0.9 dBi at 2.45 GHz and 1.7 dBi at 5.2 GHz, with a small gain variation in each of the VSWR bands.**

***Index Terms*—Card-type antenna, dual-frequency operation, finite-difference time-domain (FDTD) analysis, inverted F, inverted L.**

I. Introduction

THE increasing demand for wireless communications has been accelerating development of new antennas that operate in the required frequency bands [1]–[5]. The dual-frequency antenna is one of these new antennas, and so far numerous efforts have been made in this area [6]–[8]. For example, Wong has investigated microstrip patches for dual-frequency operation and summarized them in [9].

This paper presents an antenna that responds to the above-mentioned trend: an inverted FL antenna (InvFLA) for dual-frequency operation. The InvFLA is made of a thin conducting film, having a flat structure, as shown in Fig. 1(b), where both the radiation element (inverted F and L strip lines) in the positive y space and the ground plate (GP) in the negative y space lie in the same plane (x-y plane). In other words, the InvFLA has a co-planar ground plate, forming a card-type antenna structure.

The card-type InvFLA structure differs from the layered microstrip antenna structure for dual-frequency operation in [9], where the ground plate backs a radiation element (patch element), i.e., the patch is parallel to the ground plate. It is emphasized that the card-type structure facilitates the use of the InvFLA in PC card devices for personal computers or inside mobile phone handsets.

After a brief summary of the analysis methods, which are based on the finite-difference time-domain method (FDTDM) [10], this paper investigates an InvFLA for realizing dual-frequency operation at 2.45 and 5.2 GHz (frequencies used for wireless LAN communications). Note that the final structural parameters for the InvFLA are obtained through a step-by-step investigation of the following structures: 1) an inverted L element; 2) an inverted F element; 3) a compound of the inverted L and F elements, referred to as a *compounded LF*; 4) the compounded LF with a parasitic inverted L element; and 5) the compounded LF with a *modified* parasitic inverted L element. Also, note that the design process presented in this paper is not necessarily restricted to the specific frequencies 2.45 and 5.2 GHz. It is possible to apply the same design technique to other dual-frequency antenna designs.

For confirmation of the FDTDM results (obtained using the FDTDM computer programs developed by the authors), experimental results are presented. A good agreement between the FDTDM results and the experimental results is found.

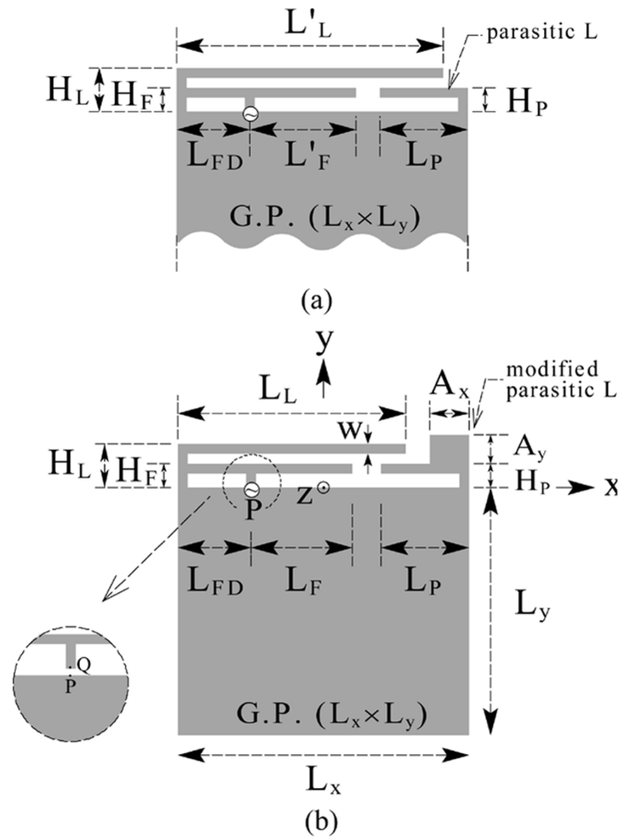

Fig. 1. Antenna structures. (a) A compound of inverted L and F elements (referred to as a *compounded LF*) with a parasitic L element above a co-planar ground plate (GP). (b) A compounded LF with a modified parasitic L element above a co-planar ground plate, referred to as the inverted FL antenna (InvFLA). The ground plate size in (a) is the same as that in (b): $L_x \times L_y = 30\ \mathrm{mm} \times 25.5\ \mathrm{mm}$.

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II. Configuration

Fig. 1(a) shows a step involved in reaching the antenna structure of Fig. 1(b). The radiation element in Fig. 1(a) is a compound of three sub-elements: an inverted L element (see inset (I) of Fig. 2, where elements α-β-γ and α'-β'-γ' are collectively referred to as the "inverted L element"), an inverted F element (see inset (II) of Fig. 2), and a parasitic inverted L element (simply referred to as a *parasitic L element*).

Fig. 1(b) is a modified version of the structure in Fig. 1(a), where a small protrusion of area $A_x \times A_y$ is added to the parasitic L element in Fig. 1(a). The structure of Fig. 1(b) is based on the inverted L and F elements, and hence it is referred to as the *inverted FL antenna* (InvFLA). It is emphasized that the InvFLA is made of a thin conducting film, where the ground plate (GP) is a co-planar ground plate, i.e., the ground plate and the radiation element lie in the same plane (x-y plane), forming a card-type structure.

The heights of the radiation sub-elements (H_L, H_F, and H_P) and the ground plate size $(L_x \times L_y)$ in Fig. 1(b) are the same as those in Fig. 1(a). However, the horizontal lengths L_L and L_F in Fig. 1(b) are slightly different from L'_L and L'_F in Fig. 1(a), respectively, as will be revealed later.

The InvFLA is excited at terminals P and Q, where the distance between P and Q is fixed to be 0.5 mm. The distance from the left side edge of the ground plate to terminal P is denoted as $L_{\rm FD}$. For the experimental work, the InvFLA is excited through a 50-ohm coaxial line without a balun circuit, where the inner conductor of the coaxial line is connected to point Q and the outer conductor is soldered to the ground plate. To facilitate a PC card implementation, a thin coaxial line can be used (a coaxial line whose outer diameter is 0.8 mm is commercially available).

The ground plate size and the strip line width of the radiation element are fixed to be $L_x \times L_y = 30\ \mathrm{mm} \times 25.5\ \mathrm{mm}$ and $w = 1\ \mathrm{mm}$, respectively, throughout this paper. There are nine structural parameters to be determined: the heights (H_L, H_F, H_P), the strip line lengths (L_L, L_F, L_P), the protrusion size (A_x, A_y), and the feed point location $L_{\rm FD}$. In this paper, the heights (H_L, H_F, H_P) are pre-selected to be small with respect to the wavelengths at 2.45 and 5.2 GHz: $(H_L, H_F, H_P) = (4.5\ \mathrm{mm},\ 2.5\ \mathrm{mm},\ 2.5\ \mathrm{mm})$. The remaining structural parameters (L_L, L_F, L_P), (A_x, A_y) and $L_{\rm FD}$ are to be determined for operation at 2.45 and 5.2 GHz.

III. Analysis and Discussion

Analysis is performed using the finite-difference time-domain method (FDTDM). For this, Yee's algorithm based on rectangular cells [10] is adopted, where the analysis space is terminated using Liao's second order absorbing boundary condition [11]. The antenna excitation is modeled by a delta-gap voltage source $V_{\rm in}(t)$, which is defined by a sine function modulated by a Gaussian function: $V_{\rm in}(t) = V_{\rm gauss}(t) \sin \omega t$, where $V_{\rm gauss}(t) = \exp\{-(t-T)/KT\}^2$, with $K = 0.29$ and $T = 0.646/f_{\rm 3dB}$. Note that $f_{\rm 3dB}$ is the frequency at which the power spectrum $(|\text{Fourier transform of } V_{\rm gauss}(t)|^2)$ drops 3 dB from its maximum value. The electric field at a far-field point, $E_{\rm Far}$ (composed of E_θ and E_ϕ), is calculated on the basis of the equivalence principle [12].

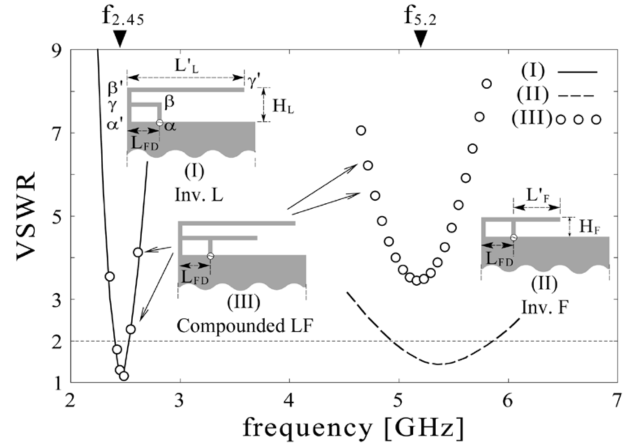

Fig. 2. VSWRs of three structures. The structural parameters for an inverted L element (I) are $(H_L,\ L'_L) = (4.5\ \mathrm{mm},\ 27.5\ \mathrm{mm})$ and $L_{\rm FD} = 7.5\ \mathrm{mm}$, and those for an inverted F element (II) are $(H_F,\ L'_F) = (2.5\ \mathrm{mm},\ 11\ \mathrm{mm})$ and $L_{\rm FD} = 7.5\ \mathrm{mm}$. A compounded LF (III) has the same structural parameters used for the sub- elements (I) and (II). The ground plate sizes in structures (I), (II), and (III) are the same: $L_x \times L_y = 30\mathrm{mm} \times 25.5\ \mathrm{mm}$.

The InvFLA is intended for installation in *mobile* equipment. In such a case, polarization purity (low cross polarization) is not required; however, an appropriate VSWR frequency response must be realized. The structural parameters for the InvFLA, Fig. 1(b), are obtained through the five steps described below, where the first three steps are rough adjustments and the fourth and fifth steps are devoted to a fine-tuning of the design.

For the first step, the inverted L element [see inset (I) of Fig. 2] is analyzed for a height of $H_L = 4.5\mathrm{mm} = 0.0368\lambda_{2.45}$, pre-selected in Section II, where $\lambda_{2.45}$ is the wavelength at 2.45 GHz $(\equiv\ f_{2.45})$. To obtain resonance around $f_{2.45}$, the horizontal length L'_L is chosen such that the total length $H_L + L'_L$ is close to one-quarter wavelength at $f_{2.45} : L'_L = 27.5\ \mathrm{mm}$ $(H_L + L'_L = 32\ \mathrm{mm} = 0.261\lambda_{2.45})$. Resonance at $f_{2.45}$ is realized by adjusting the location of feed point (distance $L_{\rm FD}$). The VSWR frequency response for $L_{\rm FD} = 7.5\ \mathrm{mm}$ is shown by the solid line in Fig. 2.

The second step is performed using the inverted F element shown in inset (II) of Fig. 2. The height H_F is chosen to be smaller than H_L for the inverted L element, described in Section II: $H_F = 2.5\ \mathrm{mm} = 0.0433\lambda_{5.2}$, where $\lambda_{5.2}$ is the wavelength at 5.2 GHz $(\equiv f_{5.2})$. The feed point is located at the same point as that for the aforementioned inverted L element $(L_{\rm FD} = 7.5\ \mathrm{mm})$. Resonance around $f_{5.2}$ is obtained by choosing the horizontal length L'_F such that the $H_F + L'_F$ is close to one-quarter wavelength at $f_{5.2}\ :\ L'_F\ =\ 11\ \mathrm{mm}$ $(H_F + L'_F = 13.5\ \mathrm{mm} = 0.234\lambda_{5.2})$. The VSWR for this structure is shown by the broken line in Fig. 2. Note that the horizontal lengths L'_F (obtained in the second step) and L'_L (obtained in the first step) are slightly changed to L_F and L_L, respectively, after the fine-tuning in the fifth step.

The third step is to compound the inverted L and F elements determined in the first and second steps, as shown in inset (III) of Fig. 2. The white dots in Fig. 2 show the VSWR for this structure. It is observed that the VSWR at $f_{2.45}$ remains almost unchanged; however the VSWR at $f_{5.2}$ deteriorates due to mutual

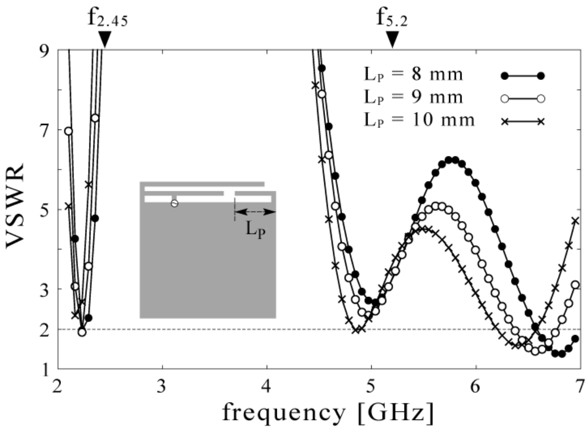

Fig. 3. Effects of the length of a parasitic L element, L_P, on the VSWR, where the structural parameters $(H_L, L'_L) = (4.5\ \mathrm{mm},\ 27.5\ \mathrm{mm})$, $(H_F, L'_F) = (2.5\ \mathrm{mm},\ 11\ \mathrm{mm})$, and $L_{\mathrm{FD}} = 7.5\ \mathrm{mm}$ are used. The ground plate size is $L_x \times L_y = 30\ \mathrm{mm} \times 25.5\ \mathrm{mm}$.

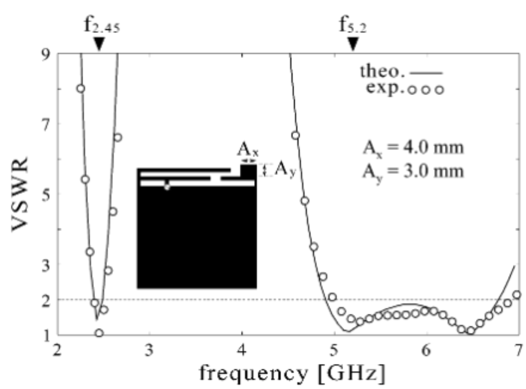

Fig. 4. VSWR for an inverted FL antenna. The structural parameters are $(H_L, L_L) = (4.5\ \mathrm{mm},\ 24.5\ \mathrm{mm})$, $(H_F, L_F) = (2.5\ \mathrm{mm},\ 10.5\ \mathrm{mm})$, $L_{\mathrm{FD}} = 7.5\ \mathrm{mm}$, $(H_P, L_P) = (2.5\ \mathrm{mm},\ 9.0\ \mathrm{mm})$, $(A_x, A_y) = (4.0\ \mathrm{mm},\ 3.0\ \mathrm{mm})$, and $(L_x \times L_y) = (30\ \mathrm{mm} \times 25.5\ \mathrm{mm})$.

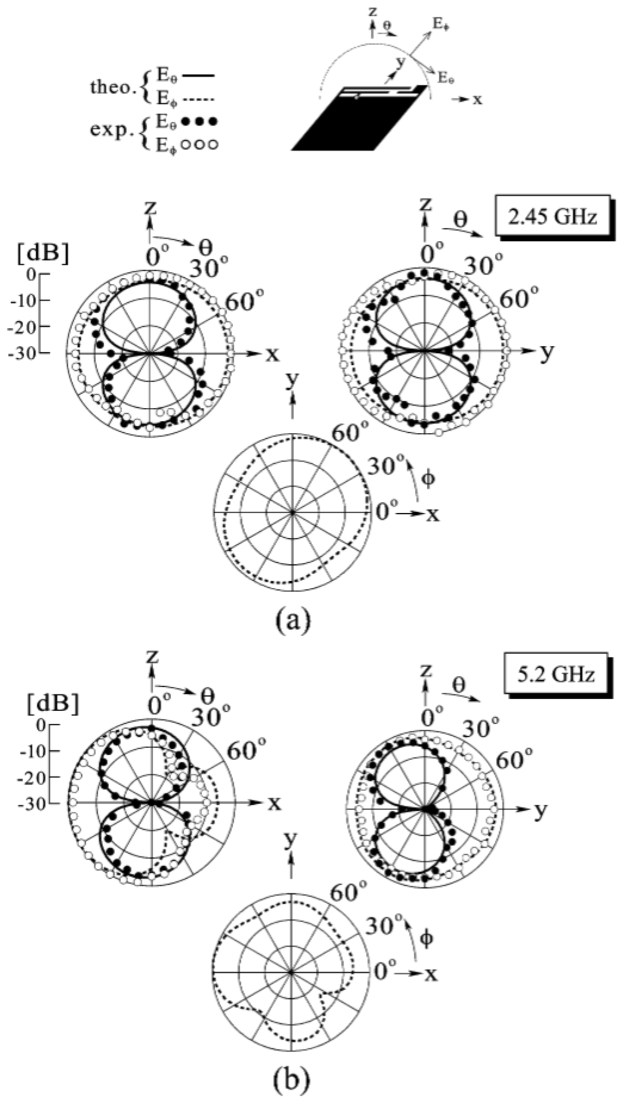

Fig. 5. Radiation patterns of an inverted FL antenna. (a) At 2.45 GHz. (b) At 5.2 GHz. The structural parameters are $(H_L, L_L) = (4.5\ \mathrm{mm},\ 24.5\ \mathrm{mm})$, $(H_F, L_F) = (2.5\ \mathrm{mm},\ 10.5\ \mathrm{mm})$, $L_{\mathrm{FD}} = 7.5\ \mathrm{mm}$, $(H_P, L_P) = (2.5\ \mathrm{mm},\ 9.0\ \mathrm{mm})$, $(A_x, A_y) = (4.0\ \mathrm{mm},\ 3.0\ \mathrm{mm})$, and $(L_x \times L_y) = (30\ \mathrm{mm} \times 25.5\ \mathrm{mm})$.

effects between the inverted L and F elements. This is overcome in the following fourth and fifth steps.

In the fourth step, a parasitic L element is added to the structure discussed in the third step, as shown in Fig. 1(a). The height of the parasitic L element is chosen to be equal to that of the inverted F element, as described in Section II: $H_P = H_F = 2.5\ \mathrm{mm}$. Fig. 3 shows the VSWR as a function of frequency for three values of the horizontal length of the parasitic L element, L_P, where the structural parameters for the inverted L and F elements are held at the values used in the third step: $(H_L, L'_L) = (4.5\ \mathrm{mm},\ 27.5\ \mathrm{mm})$, $(H_F, L'_F) = (2.5\ \mathrm{mm},\ 11\ \mathrm{mm})$, and $L_{\mathrm{FD}} = 7.5\ \mathrm{mm}$. It is found that the parasitic L element generates resonances between 6 and 7 GHz. Note that the total length of the parasitic L, $H_P + L_P$, is close to one-quarter wavelength at the frequency where the minimum VSWR for each L_P appears: $H_P + L_P = 0.238\lambda_{6.8}$ at 6.8 GHz for $L_P = 8\ \mathrm{mm}$, $H_P + L_P = 0.253\lambda_{6.6}$ at 6.6 GHz for $L_P = 9\ \mathrm{mm}$, and $H_P + L_P = 0.267\lambda_{6.4}$ at 6.4 GHz for $L_P = 10\ \mathrm{mm}$, where λ_f is the wavelength at frequency f.

At this point there are two issues: 1) the VSWR curve is slightly shifted downward with respect to frequencies $f_{2.45}$ and $f_{5.2}$; and 2) the VSWR around $f_{5.2}$ is still larger than 2. These issues are solved by the following structural modifications: 1) reduction of the original horizontal strip line lengths L'_L and L'_F, and 2) widening of the strip width of the parasitic L element. Note that the widening of the strip width is realized by making a protrusion on the parasitic L element, where part of the strip line is widened to $w + A_y$ over length A_x, as shown in Fig. 1(b).

The fifth step is to perform the aforementioned structural modifications for dual-frequency operation at 2.45 and 5.2 GHz. Using trial and error, the structural parameters are determined to be $(L_L, L_F, L_P) = (24.5\ \mathrm{mm},\ 10.5\ \mathrm{mm}, 9.0\ \mathrm{mm})$,

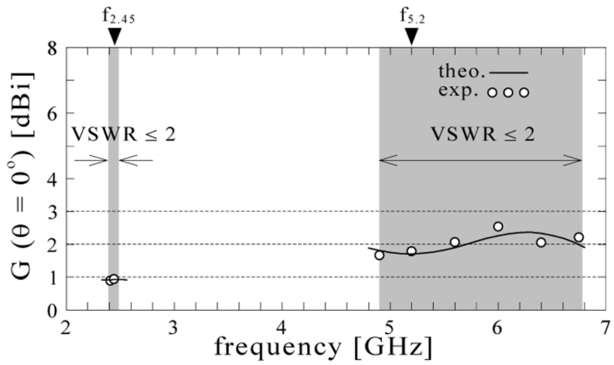

Fig. 6. Gain in the z-direction of an inverted FL antenna. The structural parameters are $(H_L, L_L) = (4.5\ \text{mm},\ 24.5\ \text{mm})$, $(H_F, L_F) = (2.5\ \text{mm},\ 10.5\ \text{mm})$, $L_{\text{FD}} = 7.5\ \text{mm}$, $(H_P, L_P) = (2.5\ \text{mm},\ 9.0\ \text{mm})$, $(A_x, A_y) = (4.0\ \text{mm},\ 3.0\ \text{mm})$, and $(L_x \times L_y) = (30\ \text{mm} \times 25.5\ \text{mm})$.

$(A_x, A_y) = (4.0\ \text{mm},\ 3.0\ \text{mm})$, and $L_{\text{FD}} = 7.5\ \text{mm}$. Note that the horizontal lengths L_L and L_F are slightly smaller than the original lengths L'_L and L'_F in Fig. 1(a), respectively. Also note that the largest antenna height $(H_P + A_y)$ is very small with respect to the wavelength: $5.5\ \text{mm} = 0.045$ wavelength at 2.45 GHz. Fig. 4 shows the frequency response of the VSWR for the InvFLA defined with these final values for the structural parameters. This figure clearly indicates dual-frequency operation at $f_{2.45}$ and $f_{5.2}$. The frequency bandwidth for a $\text{VSWR} = 2$ criterion is 4.1% for the $f_{2.45}$ band and 31.8% for the $f_{5.2}$ band. The results are confirmed by the experimental results (white dots).

Fig. 5 shows the radiation patterns at $f_{2.45}$ and $f_{5.2}$. For confirmation of the FDTDM results, experimental results in the principal planes (x-z and y-z planes) are presented. Additionally, only the FDTDM results of the radiation patterns in the x-y plane at $f_{2.45}$ and $f_{5.2}$ are presented for completeness. The radiation patterns are useful in understanding the gain characteristic in the z direction $G(\theta = 0^\circ)$, which is shown in Fig. 6 together with experimental results, where the shadowed areas in the figure show the VSWR bands. It is found that the gain (with respect to an isotropic source) is approximately 0.9 dBi at $f_{2.45}$ and approximately 1.7 dBi at $f_{5.2}$, with a small gain variation in each VSWR band. These gain values are small due to the fact that the radiation is not highly directive, as seen from the radiation pattern E_ϕ.

The difference between the gains at $f_{2.45}$ and $f_{5.2}$ (i.e., the gain in the z-direction at 2.45 GHz is smaller than that at 5.2 GHz) is attributed to the following facts: 1) the radiation pattern E_ϕ at 2.45 GHz in each of the x-z and y-z planes is more omnidirectional than that at 5.2 GHz and 2) the radiation pattern E_θ at 2.45 GHz in each of the x-z and y-z planes (having a figure-eight pattern) shows a wider half-power beam width than that at 5.2 GHz.

An omnidirectional pattern is desirable for communications between a fixed base station antenna and an antenna installed in a *mobile* device. Note that, if a more omnidirectional E_ϕ pattern (in the x-z plane) is required for the InvFLA at 5.2 GHz, this can be achieved by placing the parasitic L element just under the horizontal strip line of the inverted F [13].

IV. Conclusion

An InvFLA, made of a thin conducting film, has a card-type structure, where the radiation element is a compound of inverted L and F elements, which is adjacent to a co-planar ground plate. The design procedure for dual-frequency operation at $f = 2.45\ \text{GHz}$ and 5.2 GHz is described in five steps. In the first step, an inverted L element is designed for operation at 2.45 GHz. In the second step, an inverted F is designed for operation at 5.2 GHz. Based on these designs, a compound of the inverted L and F elements is investigated in the third step. Fine adjustment for dual-frequency operation is performed by introducing a parasitic L element in the fourth step and then modifying the parasitic L element in the fifth step.

It is found that the VSWR frequency bandwidth of the InvFLA is 4.1% around 2.45 GHz and 31.8% around 5.2 GHz. It is also revealed that the E_ϕ component of the radiation field from the InvFLA spreads out in a somewhat omnidirectional fashion. Further analysis shows that the gain variation in each VSWR band is small. The gain in the z direction (normal to the antenna plane) is 0.9 dBi at 2.45 GHz and 1.7 dBi at 5.2 GHz.

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References

[1] Y. Guo, M. Y. W. Chia, and Z. N. Chen, "Miniature built-in quad-band antennas for mobile handsets," *IEEE Antennas Wireless Propag. Lett.*, vol. 2, pp. 30–32, 2003.
[2] M. Ali, G. J. Hayes, H. Hwang, and R. A. Sadler, "Design of multiband internal antenna for third generation mobile phone handsets," *IEEE Trans. Antennas Propag.*, vol. 51, no. 7, pp. 1452–1461, Jul. 2003.
[3] Y. Guo, I. Ang, and M. Y. W. Chia, "Compact internal multiband antennas for mobile handsets," *IEEE Antennas Wireless Propag. Lett.*, vol. 2, pp. 143–146, 2003.
[4] M. F. Abedin and M. Ali, "Modifying the ground plane and its effect on planar inverted-F antennas (PIFA's) for mobile phone handsets," *IEEE Antennas Wireless Propag. Lett.*, vol. 2, pp. 226–229, 2003.
[5] Y. Kwon, J. Moon, and S. Park, "An internal triple-band planar inverted-F antenna," *IEEE Antennas Wireless Propag. Lett.*, vol. 2, pp. 341–344, 2003.
[6] D. Llorens, P. Otero, and C. C-Penalosa, "Dual-band, single CPW port, planar-slot antenna," *IEEE Trans. Antennas Propag.*, vol. 51, no. 1, pp. 137–139, Jan. 2003.
[7] S. Yeh, K. Wong, T. Chiou, and S. Fang, "Dual-band planar inverted F antenna for GSM/DCS mobile phones," *IEEE Trans. Antennas Propag.*, vol. 51, no. 5, pp. 1124–1126, May 2003.
[8] H. Chen, W. Chen, Y. Cheng, and Y. Lin, "Dualband meander monopole antenna," in *Proc. IEEE Antennas and Propagation Soc. Int. Symp.*, vol. 3, Columbus, OH, Jun. 2003, pp. 48–51.
[9] K. Wong, *Compact and Broadband Microstrip Antennas*. New York: Wiley, 2002.
[10] A. Taflove, *Computational Electrodynamics: The Finite-Difference Time Domain Method*. Norwood, MA: Artech House, 1995.
[11] Z. P. Liao, H. L. Wong, B. P. Yang, and Y. F. Yuan, "A transmitting boundary for transient wave analysis," *Science Sinica, Series A*, vol. 27, no. 10, pp. 1063–1076, 1984.
[12] C. A. Balanis, *Antenna Theory: Analysis and Design*, 2nd ed: Wiley, 1982, pp. 575–594.

[13] H. Nakano, K. Morishita, Y. Sato, H. Mimaki, and J. Yamauchi. A card-type inverted LFL antenna for dual-frequency operation. presented at Proc. IEEE-ACES Int. Conf. Wireless Communications and Applied Computational Electromagnetics. [CD-ROM] s27p03i

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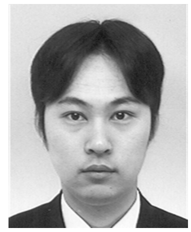

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