Design and Implementation of A Novel Rasorber for Aircraft Stealth Applications

Chandrika Sudhendra, Madhu AR, ACR Pillai
Aeronautical Development Establishment,
Defence Research Development Organization - DRDO
Bengaluru , India

Gayathri Shekar, TS Rukmini
Department of Electronics and Communication
NMIT
Bengaluru, India

KARK Rao
Department of Electronics & Communication
PES College of Engineering
Mandya, India

Abstract **– A novel rasorber based on frequency selective surfaces (FSS) for dual functions operating as stealthy FSS radome for an antenna operating at 3.7 GHz with RF transparency bandwidth of 400 MHz and also as a thin capacitive circuit radar absorber in X band with Radar Cross Section Reduction (RCSR) of 10 dB (minimum) is described. The conducting backplane of rasorber is modified by using a metallic Jerusalem cross slot FSS, which is designed to function as conducting ground plane in the radar absorber frequency range and also to function as radome with band pass spatial filtering properties in the antenna radiating band.**

Keywords—RCS, RCSR, FSS radome, Rasorber, RAS.

I. Introduction

Passive stealth design [1] of aircrafts/unmanned air vehicles (UAV) also known as radar low observables comprise i. application of radar absorbers (RA) designed as radar absorbing structures (RAS) ii. Stealthy radomes based on frequency selective surfaces (FSS) [2] iii. Antennas designed for low monostatic radar cross section (RCS) in addition to *primary shape design*. These design techniques aim at reducing the monostatic RCS of the air-vehicle.

Rasorber (Radome+Absorber) combines the functions of FSS radome and radar absorber in a single structure. As high radar transparency is required in the operating frequency band of the antenna, the rasorber should be designed with minimal transmission loss and at the same time designed for good absorption in the out-of-band frequency region of the antenna which it encloses.

We have earlier reported wide band Jaumann radar absorber [3] with RCS reduction (RCSR) of 15 dB from 2 to 18 GHz. with spacecloths [4,5] realized using novel concept of embedded passives resistor based geometrical square grid networks on dielectric substrates. In a recent paper [6], ultra wide band radar absorbers with radar reflectivity of -10 dB (minimum) from 1.7 GHz to 32 GHz. is reported.

FSS radomes need to be designed as band pass microwave spatial filters for realizing the desired RF transparency as well as out-of-band, monostatic RCSR and have been widely reported for deriving desired performance.

Capacitive circuit radar absorbers described in [7] replace band-stop resistive FSS by low-pass resistive FSS such as square patches. But hardware translation and crucial experimental verification details are not available.

In a recent paper [8], rasorber design with polarization sensitive RF transparent window is reported with radar absorption properties in X and Ku bands. The authors have resorted to design of a two layer capacitive circuit radar absorber with transmission loss of 1.9 dB at L band. But crucial practical implementation details supported by measurements are not available. In a more recent paper by Filippo Costa etal [9], a FSS radome with wideband absorbing properties is reported but once again, crucial hardware implementation and experimental verification of the design are not available.

In this paper, we describe a thin rasorber with RF transparency bandwidth of 400 MHz centered at 3.7 GHz. The single layer circuit analog radar absorber is based on resistive circular patch FSS and designed for RCSR of 10 dB in X band. The operating frequency of the antenna is specified as 3.7 GHz. with a bandwidth of 400 MHz and this paper is focused entirely on the design and reliable translation to rasorber hardware implementation and experimental verification of the design, to enable easy up scaling for aircraft applications.

The total thickness of thin rasorber presented in this paper is 4.27 mm and the weight of the prototype planar rasorber of size (280 × 280) mm is 86 gm.

II. EM Design and Simulation

The dielectric profile of rasorber is shown in Fig. 1. and a 3D sketch of rasorber is shown in Fig. 2. The design is optimized in HFSS 2014 simulation software and parametric simulation studies are presented.

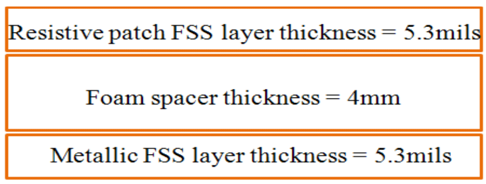

Fig.1. Dielectric profile of thin rasorber.

978-1-4799-6013-2/14/$31.00 ©2014 IEEE.

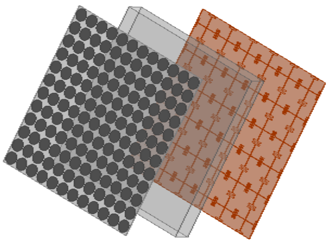

Fig. 2. 3D sketch of rasorber.

The prototype rasorber is realized as three layer sandwich construction with a resistive-capacitive FSS top layer on a thin dielectric spacer backed by the modified conducting ground plane with Jerusalem Cross Slot (JCS) FSS elements. Both FSS layers are designed and realized as infinitesimally thin (thickness = 5.3 mils) PCBs using conventional PCB design and fabrication technology. RCS measurements and RF transparency measurements are carried out in microwave anechoic chamber and simulation and measurement results are compared.

The rasorber structure design has to be optimized for realizing the dual functions of an FSS radome in the operating frequency band of the enclosed antenna combined with radar absorption properties in ***X*** band. Since the antenna is required to operate at a frequency of 3.7 GHz. with 400 MHz bandwidth, the FSS radome design needs to be optimized for minimum insertion loss with maximum RF transparency in this band.

The EM design of the top *resistive* FSS layer of rasorber has to meet maximum RF transparency in the operating band of the antenna with circular polarization. As circular polarization properties need to be derived from rasorber, a judicious choice of resistive FSS element geometry with appropriate spacing is the first step in design. From our recent paper [10], a *novel* resistive circular patch FSS was used to realize exact circular polarization performance from radar absorber with a total thickness of only 0.124λ, from 6 to 14 GHz. Hence, circular patch FSS geometry in a square grid lattice is chosen for design of the resistive FSS top layer of rasorber. It is vital not only to optimize the design for best RF transparency at 3.7 GHz, but also derive the desired radar absorption properties of 10 dB (minimum) in X band, with minimum thickness. The design has to be optimized both in terms of size of the patch and more importantly, the spacing between the patches.

The rasorber design is analyzed in full wave simulation software - HFSS. Floquet's theorem for periodic FSS enables analysis of the entire rasorber structure by simulating a unit cell. A graph of the reflectivity/RCSR of a circular patch with a foam dielectric spacer thickness of 4 mm backed by a conducting backplane is plotted in Fig. 3. A commercially available resistive sheet with surface resistivity of 100 Ω/square is used for deriving the desired absorption properties. From the figure it is observed that an RCSR (minimum) of 10 dB may be realized from 7.8 GHz. to 13.15GHz. and hence the radar absorber performance is guaranteed in X band.

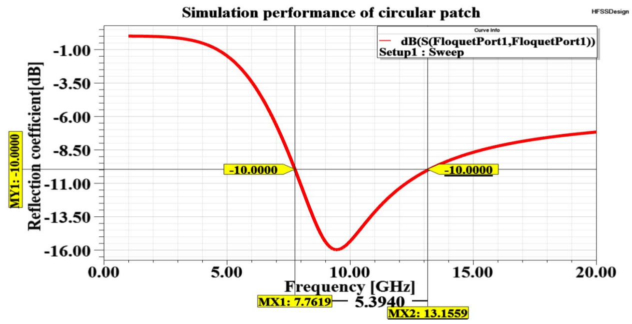

Fig. 3. Optimized RCSR simulation performance of resistive circular patch FSS.

Simultaneously, the resistive FSS design has been optimized for transmission loss (maximum) of 1 dB from 3.5 to 3.9 GHz. The optimized resistive circular patch layer dimensions are: radius of circular patch = 4 mm, unit cell size = 9mm, with a pitch of 1mm between the patches.

From [11], the physical limit of minimum thickness of a wide band dielectric radar absorber is given by the equation:

$$d \geqslant \frac{\left| \int_0^\infty \ln \left| R(\lambda) \right| d\lambda \right|}{2\pi^2} \quad \text{..........} \quad \text{..........} \quad ..(1)$$

Where, d is the total thickness of the radar absorber and R is the reflection coefficient in dB and λ is the free space wavelength. Further simplification of the above equation results in the relation: minimum thickness equal to (1/17.2) λ_0, which is equal to 2.25 mm. (λ_0- wavelength at the lowest frequency of radar absorber). The radar absorber thickness is 4.27 mm and hence does not violate the fundamental thickness limit.

A Jerusalem Cross Slot (JCS) FSS geometry in a square grid is designed for achieving the desired RF transparency with band pass spatial filter characteristics of FSS radome. The optimized simulation performance of JCS FSS based FSS radome on microwave substrate of thickness 5.3 mils with dielectric constant of 2.96 and tanδ = 0.0014 is shown in Fig. 4. From the figure it is observed that a transmission loss of 0.1 dB is obtained at 3.7 GHz. The optimized JCS FSS dimensions are: Unit cell size = 18mm with length = 16.35 mm and pitch = 1.65 mm.

Next, the *composite r*asorber structure with three layers namely the resistive circular patch FSS bonded to the foam backed JCS FSS is analyzed for its performance in HFSS. The composite rasorber performance for both TE and TM incidences is given in Fig. 5. The TE and TM performances coincide exactly for normal incidence which is attributed to the two dimensional symmetry of the JCS FSS and the circular patch FSS geometry.

In the inset of the same figure, a unit cell of the complete composite rasorber structure is also shown. Four resistive FSS patches of the top layer and one JCS slot FSS spaced by a dielectric spacer of thickness 4 mm constitute the unit cell geometry of the composite rasorber structure, to realize the desired performance.

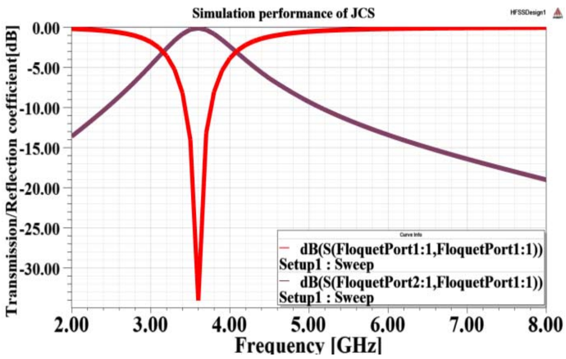

Fig. 4. Optimized simulation performance of JCS FSS of rasorber for RF transparency at 3.7 GHz.

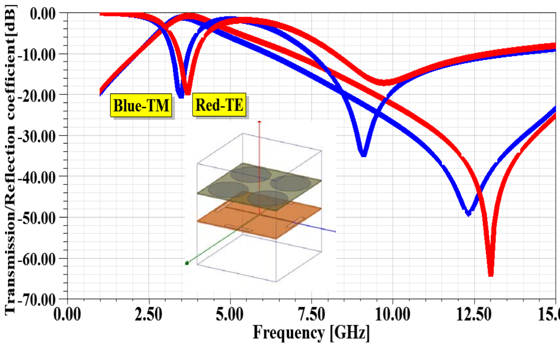

Fig. 5. Optimized rasorber simulation performance for normal incidence. *Inset: A composite unit cell shown for clarity.*

It is clear from Fig. 5 that desired radar absorber and FSS radome properties can be realized from the rasorber design. At the FSS radome/antenna center frequency of 3.7 GHz, transmission loss of 0.8 dB is obtained and an RF transparency bandwidth of 400 MHz is obtained with transmission loss of 1 dB. The radar absorber bandwidth is from 8 to 13 GHz. with absorption/RCSR of 10 dB (minimum). At the design center frequency of 10 GHz. of rasorber, a peak radar reflectivity of 17 dB is predicted.

Various parametric simulation studies are carried out on rasorber for assessing the performance with variation in design parameters such as Angles Of Incidence (AOI), radii of the circular patches, width of the JCS FSS and also fabrication tolerances such as variation in foam thickness and the results will be summarized in a later section. A plot of variation of rasorber performance at 30 ° AOI for TE and TM polarization is given in Figs. 6 and 7 respectively.

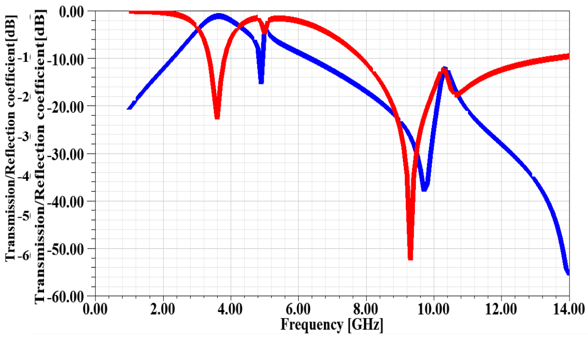

Fig. 6. Simulation performance at 30° AOI. *TE incidence.*

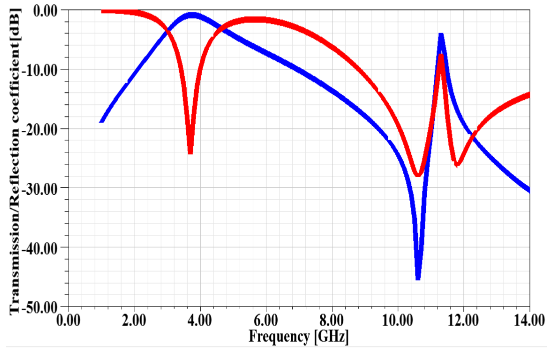

Fig. 7. Simulation performance at 30° AOI. *TM incidence.*

III. FSS PCB FABRICATION, RASORBER CONSTRUCTION AND MICROWAVE MEASUREMENTS

Both the JCS FSS and resistive FSS top layer of rasorber are designed as infinitesimally thin (thickness = 5.3 mils) PCBs using ECAD PCB layout design tool, *Visula v. 2.3.* Microwave substrates with ε_r = 2.96 and tanδ = 0.014 is used for fabrication of both the FSS layers as high performance PCBs. Conventional but standardized PCB fabrication process is used for fabrication of the FSS. The resistive patch FSS PCB is bonded to a *Rohacel* foam dielectric spacer of thickness 4 mm using a double sided very thin tape which is backed by an electrically thin (thickness = 5.3 mils) JCS FSS PCB layer. Photograph of the two fabricated FSS PCB layers of size (280 × 280) mm are shown in Fig. 8. The assembled prototype planar rasorber is shown in Fig. 9. Weight of the panel rasorber is 86 gm.

RCS experiments are carried out on panel rasorber in microwave anechoic chamber to verify the design and simulation using monostatic measurement setup. Automated digital recorder interfaced to an RF synthesized source through a desk top computer completes the measurement setup.

The planar rasorber is securely placed at the centre of the quiet zone on an RF transparent, low loss thermocol stand connected to a single axis positioner. With this setup, continuous rotation from 0 to 360 degrees is possible in the azimuth plane. The front side of the rasorber is aligned to 0°

Fig. 8.Photograph of constituent FSS PCB layers of rasorber.

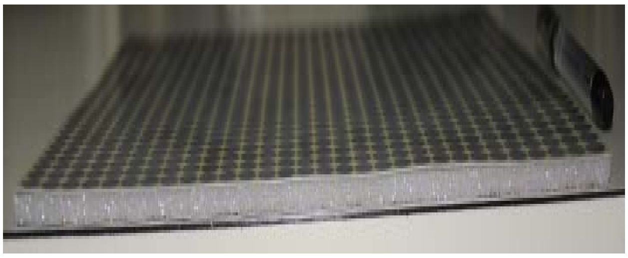

Fig. 9 The prototype panel rasorber.

of the polar chart and the RCS reading from the modified conducting backplane serves as reference with which the RCS returns from front side of rasorber are compared. Ensuring vectorial cancellation of the 'background' at each measurement frequency, RCS returns of rasorber are recorded in X band. A representative RCS plot of rasorber is shown in Fig. 10. The FSS radome band pass spatial filter characteristics or the radar transparency of rasorber in the frequency range of 3.5 GHz. to 3.9 GHz. is measured by carrying out insertion loss measurements on rasorber for both TE and TM polarization of the impinging EM wave and readings are plotted in Fig. 11. Two high directivity horn antennas and spectrum analyzer are used for insertion loss measurements. Plane wave illumination is ensured by placing the rasorber in the far field of the transmitting horn. The three criteria for the rasorber panel to be in the far field is satisfied namely,

$$r >> d$$

$$r >> kd^2 \quad \text{and}$$

$$r >> \lambda$$

Where, r is the distance from the rasorber to the antenna and d is the largest linear antenna dimension and k is the wave number. A matlab graph of simulated and measured insertion loss of the FSS radome is shown in Fig. 11.

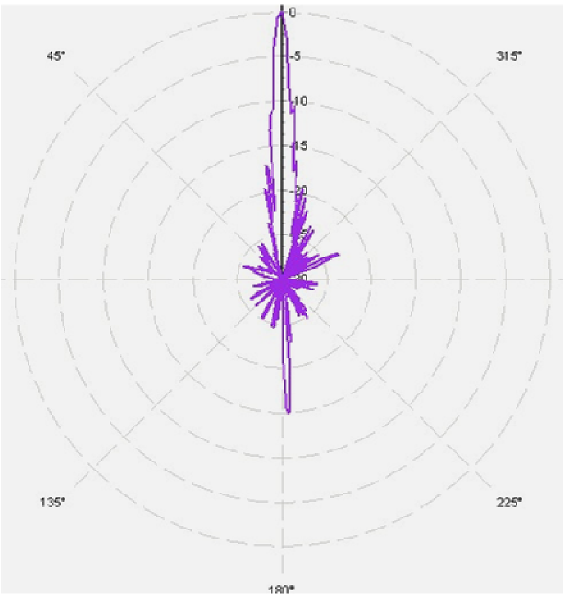

Fig. 10. Representative RCS measurement plot of rasorber. Frequency: 10 GHz; Polarization: Vertical.

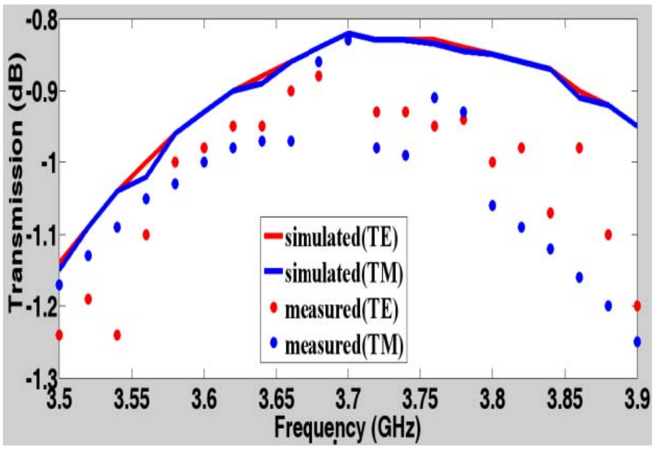

Fig. 11. Comparison of simulated and measured results of RF transparency of rasorber.

IV. DISCUSSION OF RESULTS

i. A thin planar prototype rasorber designed for combining the functions of FSS radome and radar absorber is reported in this paper. The simulation results of the composite rasorber structure presented in Fig. 5 for normal incidence and RCS measurement results in X band agree to the tune of 0.5 to 1 dB. An RCSR of 15 dBsm is measured at 10 GHz. A measured RCS plot of rasorber at 10 GHz. is shown in fig. 10. RCS measurements have been carried out in X band and results are available. The radar absorption requirements in X band from rasorber have been met and the design satisfies all the requirements.

ii. From Fig. 11, it is observed that the measured insertion loss readings of the FSS radome in the operating frequency range from 3.7 GHz. to 3.9 GHz. agree to the tune of 0.2 to 0.3 dB, indicating accurate translation of design to hardware through standard process.

iii. It is noted from Fig. 6 that with variation in angle of incidence, 10 dB radar absorption bandwidth is preserved for 30° AOI, for TE polarization and the RF transparency properties are preserved without any degradation in performance.

iv. From Fig. 7, with AOI of 30°, for TM polarization, the RF transparency from 3.5 GHz. to 3.9 GHz. is preserved with no degradation in radome characteristics, whereas a slight decrease in radar absorption from 10 dB to 9 dB at 11.2 GHz. is observed.

v. Extensive parametric simulation studies were carried out in HFSS to quantify the effects of both variation in design parameters and also to account for tolerances in fabrication. Variations in the length of the JCS FSS result in shift of resonant frequency. Increase in foam thickness results in increased radar absorber bandwidth. Since radar absorption properties were required in X band, the foam thickness was optimized to 4 mm.

vi. Since a superstrate becomes vital for air vehicle applications, simulation studies carried out on rasorber by using a substrate with ε_r = 2.2, tanδ=0.0019 and thickness

5.3 mils resulted in a downward shift of the radome operating frequency from 3.7 GHz. to 3.2 GHz, with an increase in radar absorption bandwidth from 6 GHz. to 13 GHz. However since the antenna was designed for 3.7 GHz. the design was iterated for preserving the centre frequency of operation of the radome at 3.7 GHz without degrading the RF transparency properties of the radome. The radar absorption properties, however, have improved with 10 dB radar absorber bandwidth from 7.5 GHz. to 13 GHz.

V. CONCLUSION

A planar rasorber with dual functions of both radar absorber and FSS radome is designed and implemented. The two FSS layers of rasorber realized as electrically very thin PCBs with low loss foam dielectric spacer have resulted in substantial reduction in thickness and weight. Best RCSR of 15dB has been measured at 10 GHz. The thin rasorber may be used for realizing radome functions in lower microwave frequency bands such as L and C bands and radar absorption properties in higher microwave frequency bands such as X band. Since application of superstrate becomes crucial for air vehicle applications, the design has been re-iterated for preserving the properties. The low profile and weight of the rasorber combined with low density, structural foam and electrically very thin, low loss substrates in a sandwich construction enable easy up scaling for applications in aircraft stealth.

ACKNOWLEDGMENT

The authors convey their grateful thanks to Shri. P Srikumar, Outstanding Scientist and Director, ADE for his continued guidance, encouragement, support and according permission to present this paper in the conference. We place on record our hearty thanks to Shri. K.G. Ramamanohar, Scientist G, Group Director, for his unstinted support and guidance. We thank Dr. V. Ramachandra, Sc. G, Head, FTTT division and Mr. Diptiman Biswas, Sc. E, ADE for providing the RCS measurement facility.

REFERENCES

[1] Knott EF, Shaeffer JF, Tuley M (1993) Radar cross section. Artech House, USA.

[2] Benedict A. Munk, Frequency Selective Surfaces: Theory and Design. New York: Wiley-Interscience, 2000.

[3] Chandrika Sudhendra, AK Mohanty, V.Mahule, ACR Pillai and KARK Rao, “Embedded Passives Resistor Grid Networks Based Novel Wideband Radar Absorber”, *DOI: 10.1109 /CONECCT.2014.6740359,* pp.1-4, IEEE Intnl. Conf. on Elect. Computin and Commn. Technologies – CONECCT 2014.

[4] Abouzhara, “Automated Wide-Band Surface Resistivity Measurements of Resistive Sheets”, *IEEE Trans. on Instmn. and Mea.,* vol. IM 36, pp. 1031-1035, 1987.

[5] Chandrika Sudhendra, V.Mahule, AK Mohanty and ACR Pillai, “A Novel Space Cloth Using Resistor Grid Network for Radar Absorbers in Stealth Applications”*, DOI:10.1109/ICCSP.2011.5739405,* pp. 83-86*, Proc. ICCSP 2011*.

[6] Chandrika Sudhendra, Madhu AR, ACR Pillai, KARK Rao and T.S. Rukmini, “A Novel Ultra Wide Band Radar Absorber Based on Hexagonal Resistive Patch FSS”, in Applied Electromagnetics Conference –AEMC 2013, Dec. 18-20, 2013, Bhubaneswar.

[7] Alireza Kazem Zadeh and Anders Karlsson, “Capacitive circuit Method for Fast and Efficient Design of Wideband Radar Absorbers”, *IEEE Trans. Antennas Propag.,* vol. 57, no. 8, pp. 2307–2314, Aug. 2009.

[8] A. Motevasselian and BLG Jonsson, “Design of a widband Rasorber with a polarisation sensitive transparent window”, IET Microw. Antennas Propag., 2012, Vol. 6, Iss. 7, pp.747-755, DOI:10.1049/iet-map.2011.0444.

[9] Filippo Costa and Agostino Monorchio, “A Frequency Selective Radome With Wideband Absorbing Properties”, *IEEE Trans. Antennas Propag.,* vol. 60, no.6,June 2012.

[10] Chandrika Sudhendra, Madhu AR, ACR Pillai and KARK Rao, “A Novel 6 to 14 GHz. Thin Radar Absorber Based on Circular Resistive Patch FSS”, DOI,10.1109/CCUBE.2013.6718574, pp. 1-4, 2013.

[11] K. N. Rozanov, “Ultimate thickness to bandwidth ratio of radar absorbers,” *IEEE Trans. Antennas Propag.,* vol. 48, no. 8, pp. 1230–1234, Aug. 2000.