A Low-Profile Broadband Antenna for Wireless Communications

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ABSTRACT A low-profile microwave antenna suitable for high data-rate radio communications is presented. Although the size, cost, and efficiency are comparable to the microstrip patch, the 2:1 VSWR bandwidth of the antenna presented here exceeds 20%. The radiation pattern of the antenna does not change appreciably within the bandwidth, and the efficiency remains above 70% within the bandwidth. Measurements on antennas around 2 and 4 GHz are presented, as well as theoretical results using a full-wave analysis.

I. Introduction

Although microstrip patch antennas are low-profile and inexpensive, they have limited bandwidths of typically a few percent, and this has been the most limiting factor for their extensive use. Various techniques for increasing the bandwidth have been used: reducing the Q of the circuit by increasing the substrate height and/or lowering its dielectric constant [1]; using circular and square ring configurations [2]; using multiple coupled resonators on the same substrate [3,4,5]; using multiple vertically coupled resonators [6]; and using log periodically grated patches [7]. The largest reported bandwidths are around 20%. The disadvantages of the listed techniques include change in the radiation pattern over the bandwidth, complicated multilayer structures, and large antenna size. In this work, we present a new type of planar antenna, which is a combination of a wire antenna array and a microstrip patch antenna. The antenna is slightly smaller than the standard resonant patch and exhibits a 2:1 VSWR bandwidth of approximately 23%. The radiation pattern does not change appreciably within the bandwidth, and the polarization of the radiation field is linear with measured cross-polarization ratios between -16 dB and -23 dB. Rather than being resonant at a single frequency, the presented antenna has a broad resonance that can be controlled by several antenna design parameters. The theoretical standing wave ratios, efficiencies, and far-field patterns of these antennas, as well as measured results obtained for several antenna experimental models, are presented.

II. Antenna and Feed Description

The antenna geometry is shown in Fig. 1. A planar array of narrow printed conducting strips (or thin wires) is located

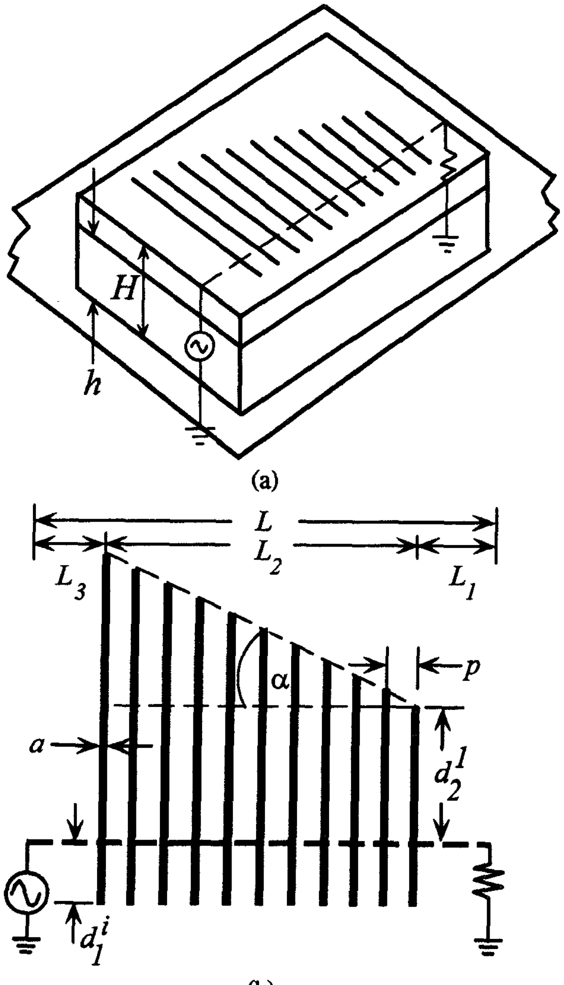

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Figure 1: *The geometry of an N-element quasi-microstrip antenna.* (a) *A planar array of narrow printed conducting strips is located above a feed strip of length L above an infinite ground plane. The feed line is connected to a generator at one end and terminated in its characteristic impedance at the other end.* (b) *Top view of the antenna, with inter-element spacing, p, much smaller than the wavelength and much greater than the width of the strips. There are N radiating elements printed on the upper dielectric.*

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above a feed strip of length L above an infinite ground plane. The feed strip and the ground plane form a transmission line connected to a generator on one end and terminated in its characteristic impedance Z_0 on the other end. We call this a quasi-microstrip antenna because the planar antenna structure is less than $\lambda / 10$ above the ground plane, but the antenna is a set of thin cylindrical wires or narrow printed strips instead of a metal patch.

The antenna has an anisotropic character since the current can flow only along the thin conducting strips. The antenna has N elements with inter-element spacing, p, that is much smaller than the wavelength but much larger than the strip width a (or wire radius r). The lengths d_1^i and d_2^i of the i-th element in the array are on opposite sides of the feed. The feed line is at a height h, and the strips at a height H above the ground plane. The radiating part of the antenna has dimension L_2, and is located a distance L_1 from the termination and L_3 from the generator. The taper of the radiating elements' lengths is governed by the angle $\alpha = \arctan[(d_2^N - d_2^1) / L_2]$.

The antenna was analyzed and designed using the CAD program *WireZeus* [9]. Briefly, Hallén's generalized integral equation for the current distrubution along arbitrarily interconnected straight wire segments is solved by the point matching technique. Entire (or almost entire) domain polynomial basis functions are used for the current distribution. Each segment may have a lumped generator and/or impedance at one of its ends, and may also have a distributed impedance along its length. Conductive planes are taken into account by the image method. In the case of narrow strips printed on a dielectric substrate, the program uses a cylindrical wire with an equivalent radius and effective magnetic coating [10].

Optimization of substrate heights, h and H, was done for a radiating element 0.2 mm in radius above a feed line made of the same wire and placed at the center of the feed. The impedance of the feed line alone is 283 Ω for the case of air dielectric layers. The efficiency of the feed as an antenna was computed as a function of h to be less than 4.4%, and the gain was less than -8 dBi. The efficiency of a single radiating strip perpendicular to and centered on a 9 cm feed line at 2 GHz as a function of the strip length is shown in Fig. 2a. The optimal length of the radiating wire is seen to be about $0.46\lambda_0$ (approximately the first resonant length). Fig. 2b shows the antenna efficiency versus feed position (in wavelengths) along the length of the radiating wire (i.e. d_1 / λ in Fig. 1) for $(d_1 + d_2) = 7$ cm. It should be noted that the optimal feed position is quite broad—between 0.02λ and 0.1λ.

As a result of these calculations, the following configurations were analyzed, fabricated, and measured:

(A) Both dielectrics air (styrofoam), $h = 8$ mm, $H = 9$ mm, d_1=10 mm, and $\alpha = 11°$. There are $N = 11$ elements and the period is $p = 5$ mm. The feed is #30 (AWG) wire, and the radiating strips are copper tape, 1 mm wide. The design frequency is 2 GHz. The terminating resistor is 280 Ω. The overall size (including the ground plane) is 10 cm × 9 cm, which is approximately $0.35\lambda_0^2$.

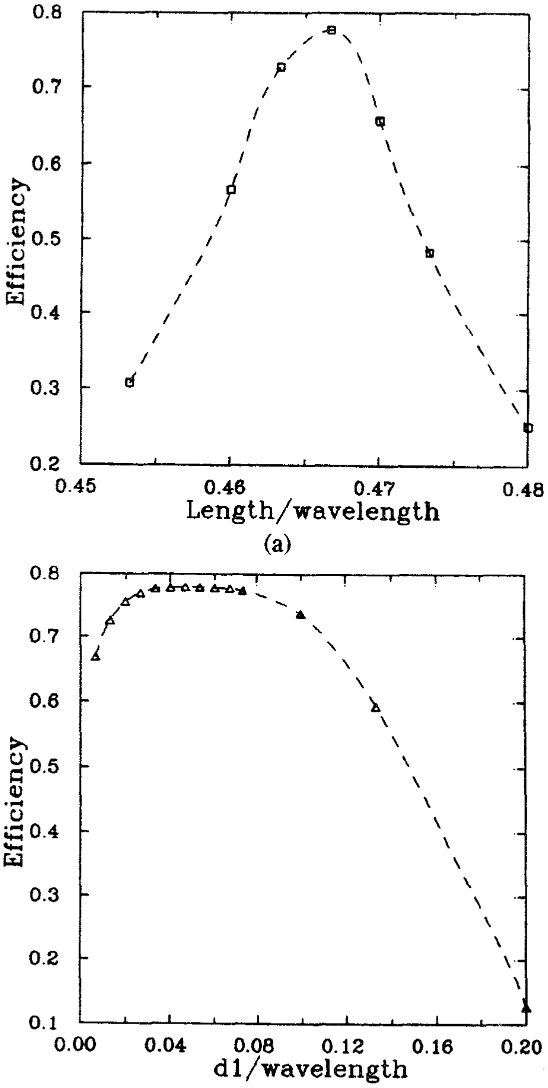

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Figure 2: (a) *Efficiency of a single radiating wire 0.2 mm in radius at 2 GHz, as a function of the total wire length in wavelengths, with $d_1 = 5$ mm, $h = 8$ mm, and $H = 9$ mm.* (b) *Efficiency of a single radiating wire versus the position (in wavelengths) of the feed along the wire (d_1), for $(d_1 + d_2) = 7$ cm, h =8 mm, and $H = 9$ mm. The radius of both feed and radiating wire is 0.2 mm.*

(B) The lower dielectric is air and the top dielectric is a Duroid® substrate 0.508 mm thick with $\varepsilon_r = 2.2$, $h = 2.5$ cm, a 200 Ω termination, and $\alpha = 16°$. The number of radiating strips is $N = 19$ and the period is $p = 3.9$ mm. The feed is printed on the bottom of the dielectric substrate and the radiating strips are on the top of this substrate. All of the printed lines are 1 mm wide after fabrication. The design frequency is 1.9 GHz. A microstrip matching circuit is designed for this antenna and located on the back side of the ground plane in order to conserve area.

(C) Designed for operation near 4 GHz with a 120 Ω termination, $h = 5$ mm, $H = 5.5$ mm, $d_l = 5$ mm, $\alpha = 18°$, $p = 3$ mm $= 0.04\lambda$, and $N = 13$ radiating elements. The top substrate has a permittivity of 2.2. The overall size of this antenna, including the ground plane and the feed, is 5.5 cm × 5.5 cm, which is approximately $0.5\lambda_0^2$. The microstrip matching circuit in this model is on the same side of the ground plane as the antenna.

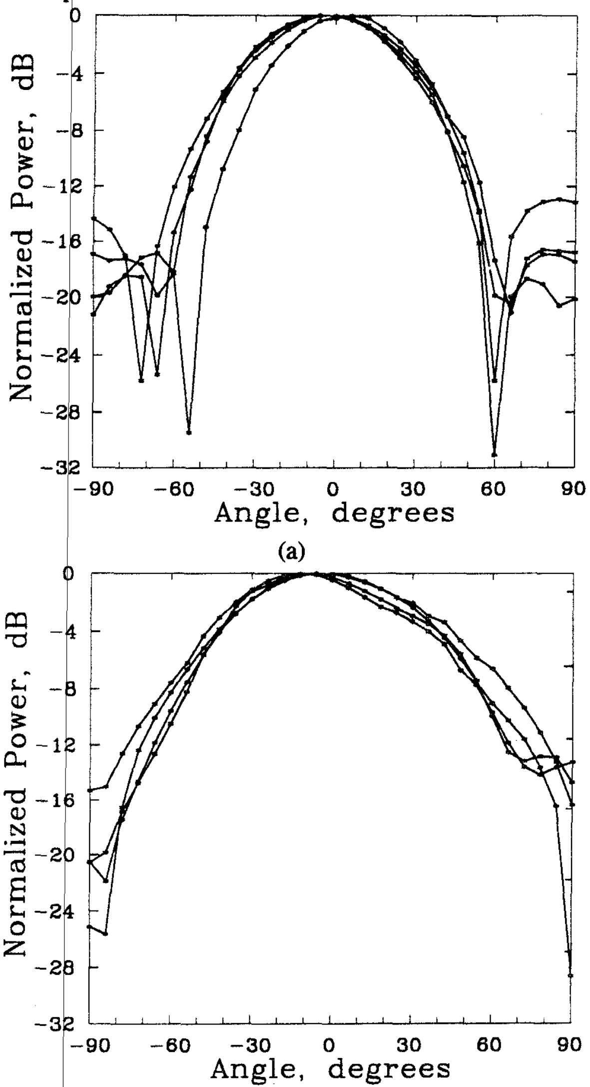

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Figure 3: *Measured radiation patterns of antenna (A) at 1.5, 1.7, 1.9, and 2.1 GHz in the E-Plane* (a) *and the H-Plane* (b). *The antenna was measured as a receiver and the received power at the measured pattern peak varied by less than 3.4 dB in this frequency range.*

III. Analysis and Measurements

Since no matching circuit was designed for antenna (A), only radiation patterns for this antenna were measured. The patterns were measured in an anechoic chamber with a computer-controlled rotation (measurements taken every 3°) of the antenna in the planes of interest. The measured patterns, shown in Fig. 3, show little variation between 1.5 and 2.1 GHz, which is more than a 40% bandwidth.

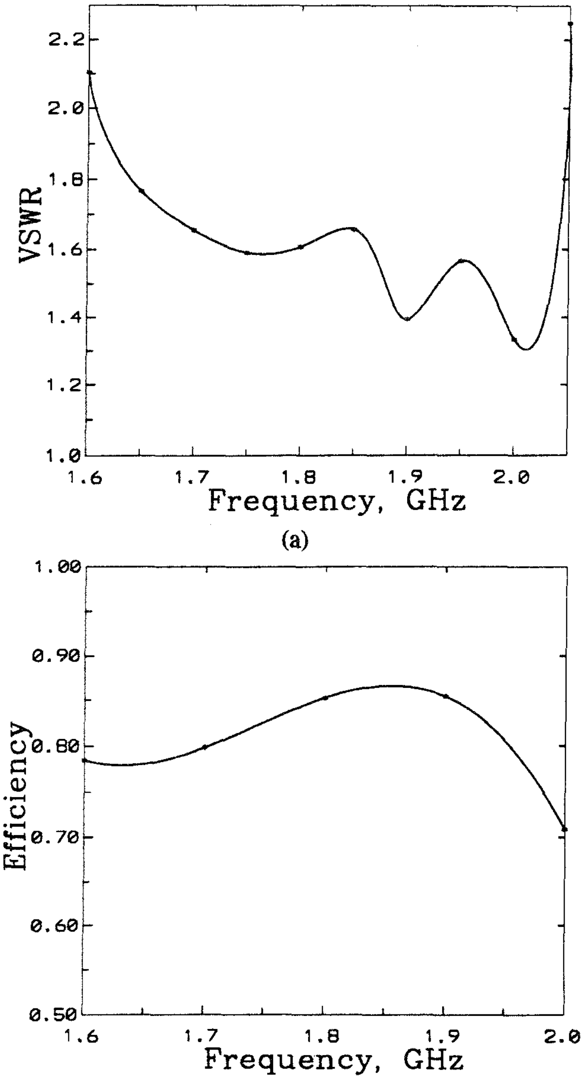

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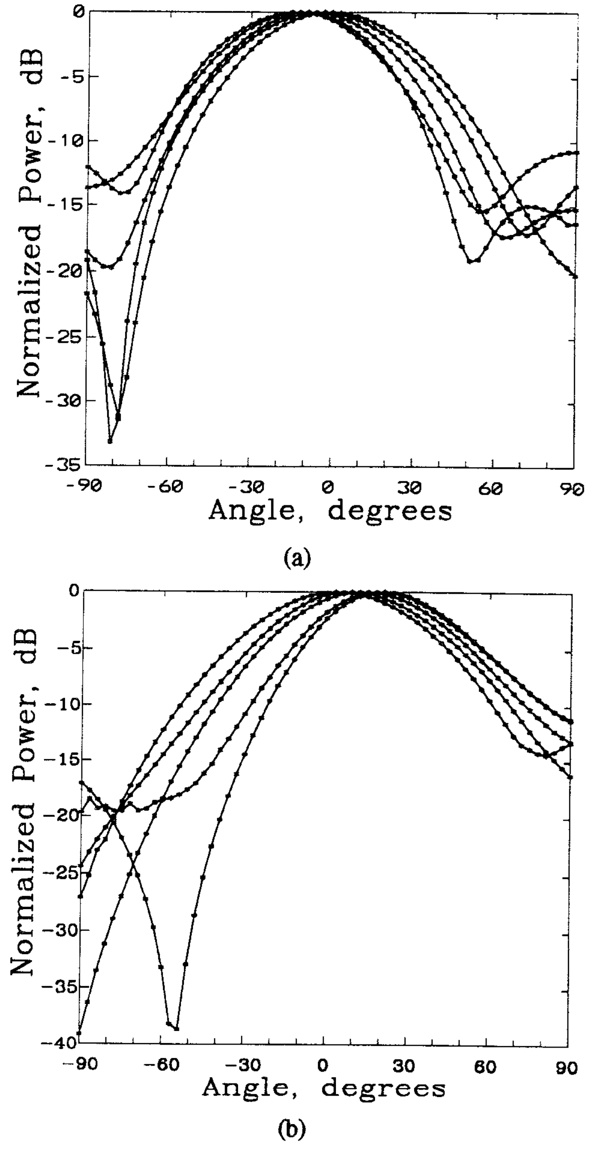
Figure 4: (a) *Measured VSWR for antenna (B) with a microstrip matching circuit. The 2:1 VSWR bandwidth is 23%.* (b) *Measured efficiency for this same antenna between 1.6 and 2.0 GHz. The efficiency was measured by matching the termination end of the antenna to a power meter in order to measure power absorbed by the lumped resistor.*

The antenna was measured as a receiver and the received power at the pattern peak varied by less than 3.4 dB within this bandwidth. With the available equipment, it was not possible to measure the full three-dimensional antenna pattern and so the efficiency could not be measured. The theoretical efficiency ranges from 79% to 91% over the antenna's bandwidth. When the generator and termination resistor are interchanged, the efficiency and patterns degrade appreciably. The predicted efficiencies then lie between 57% and 62%, and the measured received power is reduced, on average, by 3.4 dB.



(a)

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Figure 5: *Measured E-plane* (a) *and H-plane* (b) *patterns for antenna (B) over the frequency range 1.6–2.0 GHz. Received power at the pattern peak varied by 2.7 dB over this frequency range.*

The VSWR of antenna (B), measured on an HP8510 network analyzer, is shown in Fig. 4a. Fig. 5 shows the E-plane and H-plane patterns for this antenna between 1.6 and 2.0 GHz. This antenna exhibited a 2:1 VSWR bandwidth of 23% and the measured efficiency within this bandwidth was above 70%, as shown in Fig. 4b.

The efficiency of antenna (B) was measured by replacing the lumped resistor with a microstrip matching ciruit. One port of this matching circuit provided a 200 Ω impedance to the antenna, while the other port was connected to an HP437B power meter. Neglecting conductor and dielectric losses, power delivered to the antenna is either reflected, absorbed by the resistor, or radiated into space. Reflected power is accounted for by the VSWR, while power absorbed by the resistor is measured by the HP437B. Thus, input power and

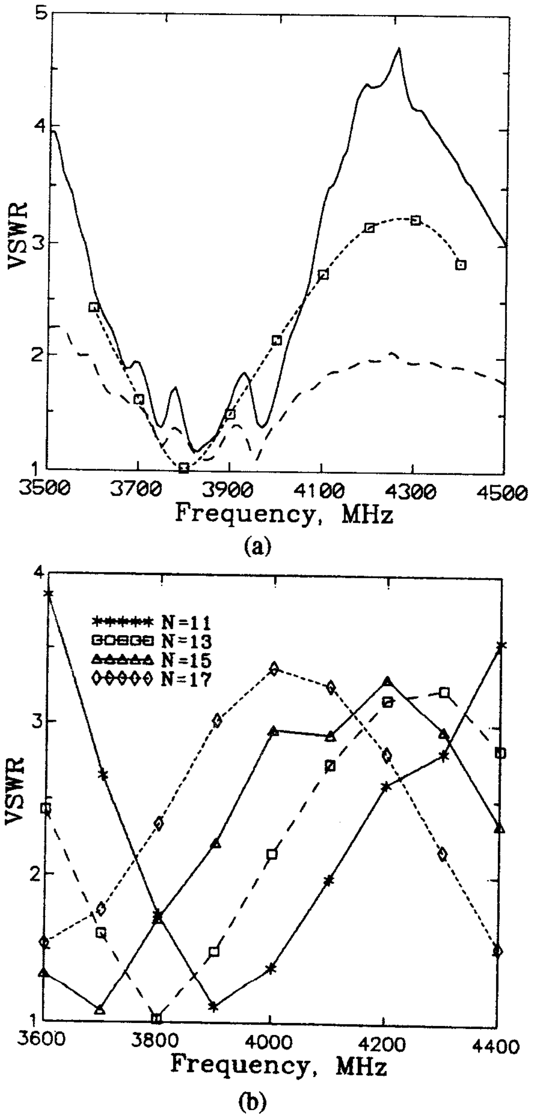

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Figure 6: (a) *Measured VSWR for antenna (C) with (dashed line) and without (solid line) a microstrip matching circuit. The dotted line shows the predicted, unmatched VSWR.* (b) *The computed frequency dependence of the VSWR of antenna (C) with p = 4 mm, α = 18.4° and the number of radiating strips, N, as a parameter.*

radiated power become known quantities and the efficiency of this antenna can be directly measured, as shown in Fig. 4b. Given the efficiency and radiation patterns of the antenna, the gain at 1.9 GHz was calculated to be 8.7 dBi.

Fig. 6a shows the measured and predicted VSWR of antenna (C) with and without the presence of a two-section microstrip matching circuit. The antenna has a bandwidth of 23%, and the predicted efficiency within the bandwidth varies between 80% and 95%.

The measured and calculated radiation patterns are similar to those shown in Fig. 5, indicating that typical 3-dB beamwidths for all of the presented antennas are between 50° and 60° in the H-planes and E-planes, respectively. The antennas are linearly polarized with a measured cross-polarized power at the pattern peak between 16 and 23 dB below the co-polarized power.

There are several geometrical parameters that can be varied in the presented antenna. Although the upper substrate thickness and permittivity can also be varied, they were adopted to be 0.5 mm and 2.2, respectively. The lengths L_1 and L_3 were also fixed, with a value of 10 mm each. The inter-element spacing (p), the number of elements (N), and the taper angle (α), were not randomly chosen in the three experimental antennas. For example, in antenna (C), the inter-element spacing, number of strips, and taper angle were considered as parameters one at a time. The number of strips was adopted to be odd, with the middle strip of constant length $(d_1 + d_2) = (0.5 + 2.7)$ cm.

Although antenna (C) was first fabricated and measured with $p = 3$ mm, we present here the results of the interactive optimization for $p = 4$ mm. The dependence of VSWR on frequency and on the number of radiating elements, with $\alpha = 18.4°$, is depicted in Fig. 6b. It is seen that the optimum number of radiating strips in this case is 13. The analysis was performed on a 486 50 MHz personal computer and typical run times were below ten seconds per frequency point.

IV. Acknowledgements

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