Novel Dual-Frequency and Broad-Band Designs of Slot-Loaded Equilateral Triangular Microstrip Antennas

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***Abstract*—By loading properly arranged slots in an equilateral-triangular microstrip patch, novel dual-frequency and broad-band operations of a single-feed triangular microstrip antenna are presented. For dual-frequency operation, the proposed design is achieved by loading two pair of narrow slots in the triangular patch, one embedded close to the side edges of the patch and the other inserted at the bottom edge of the patch. The obtained two operating frequencies are of same polarization planes and by varying the positions and lengths of the inserted slots at the bottom edge of the patch, a tunable frequency ratio of the two frequencies ranging from about 1.16 to 2.06 is obtained. Furthermore, it is found that by protruding a narrow slot out of the embedded slots close to the side edges, broad-band operation of the triangular microstrip antenna near its fundamental resonant mode can be achieved. Results show that the antenna bandwidth of the proposed broad-band design can be greater than 2.6 times that of a conventional triangular microstrip antenna. Details of the proposed dual-frequency and broad-band designs are described and typical experimental results are presented and discussed.**

***Index Terms*—Broad-band operation, dual-frequency, microstrip antenna.**

I. Introduction

THE dual-frequency design of a single-feed rectangular microstrip antenna with a pair of narrow slots placed close to its radiating edges has recently been reported [1]. The two operating frequencies, having similar radiation characteristics and same polarization planes, are the resonant frequencies of the TM_{10} and TM_{30} modes. The frequency ratio of the two operating frequencies is generally within the range of 1.6–2.0 [1]. This frequency-ratio restriction imposes a limitation for such a dual-frequency design in some applications where lower frequency ratio is required. In this paper, we propose that by applying a similar but different slot-loading technique [2]–[4] to an equilateral-triangular microstrip antenna, dual-frequency operation with an extended frequency-ratio range, as compared to that of a slot-loaded rectangular microstrip antenna [1], can be obtained. This proposed dual-frequency design is achieved by loading two pairs of narrow slots in the triangular patch, with one pair of the slots embedded close to the side edges of the patch and the other pair inserted at the bottom edge of the patch [see Fig. 1(b); Fig. 1(a) can be considered as a special case of Fig. 1(b)]. The two operating frequencies in this case are associated to the resonant modes of TM_{10} and TM_{20} [5], [6]. It is found that due to the slots embedded close to the side edges, the radiation pattern of the TM_{20} mode, which usually exhibits a slight dip in the broadside direction [5], is removed and become similar to that of the TM_{10} mode. As for inserting the pair of slots at the bottom edge of the patch, various frequency ratios of the two operating frequencies can be obtained by varying the length and position of the inserted slots.

Moreover, it is found that by further protruding a narrow slot out of the embedded slots close to the side edges [see Fig. 1(c)], the frequency ratio of the two frequencies can be adjusted to be close to unity, which means broad-band radiation is obtained. This broad-band operation is especially important for the triangular microstrip antenna [7]–[9]. This is because although the conventional triangular microstrip antenna has the advantage of physically smaller for operating at a given frequency, as compared to the rectangular or circular microstrip antennas, it also exhibits a smaller antenna bandwidth than the rectangular or circular ones. With the present design technique, the proposed triangular microstrip antenna can have a wider operating bandwidth with a smaller antenna size as compared to the conventional rectangular or circular microstrip antennas. Details of the proposed antenna designs are described and experimental results for the obtained dual-frequency and broad-band performance are presented and discussed.

II. Antenna Configurations

A. Dual-Frequency Design

The geometry of the proposed dual-frequency design is depicted in Fig. 1(a) and (b). The proposed design in Fig. 1(a) is denoted here as a simple slot-loaded triangular microstrip antenna and can be treated as a special case of the design in Fig. 1(b). For both cases, the triangular patch is assumed to be equilateral with a side length of d and is printed on a substrate of thickness h and relative permittivity ε_r. The pair of slots (denoted as slot 1 in this study), having dimensions $(\ell_1 \times w)$, are placed in parallel to the side edges of the triangular patch, with a small distance d_1 away from the side edges. In Fig. 1(b), another pair of slots (denoted as slot 2 here) with dimensions $(\ell_2 \times w)$ are inserted at the bottom edge of the triangular patch and centered with respect to the center line $(\overline{AB})$ of the patch with a spacing d_2.

These two pairs of slots are also of narrow width, i.e., $w \ll \ell_1, \ell_2$. The length of slot 1 is selected to be about 0.8 times the

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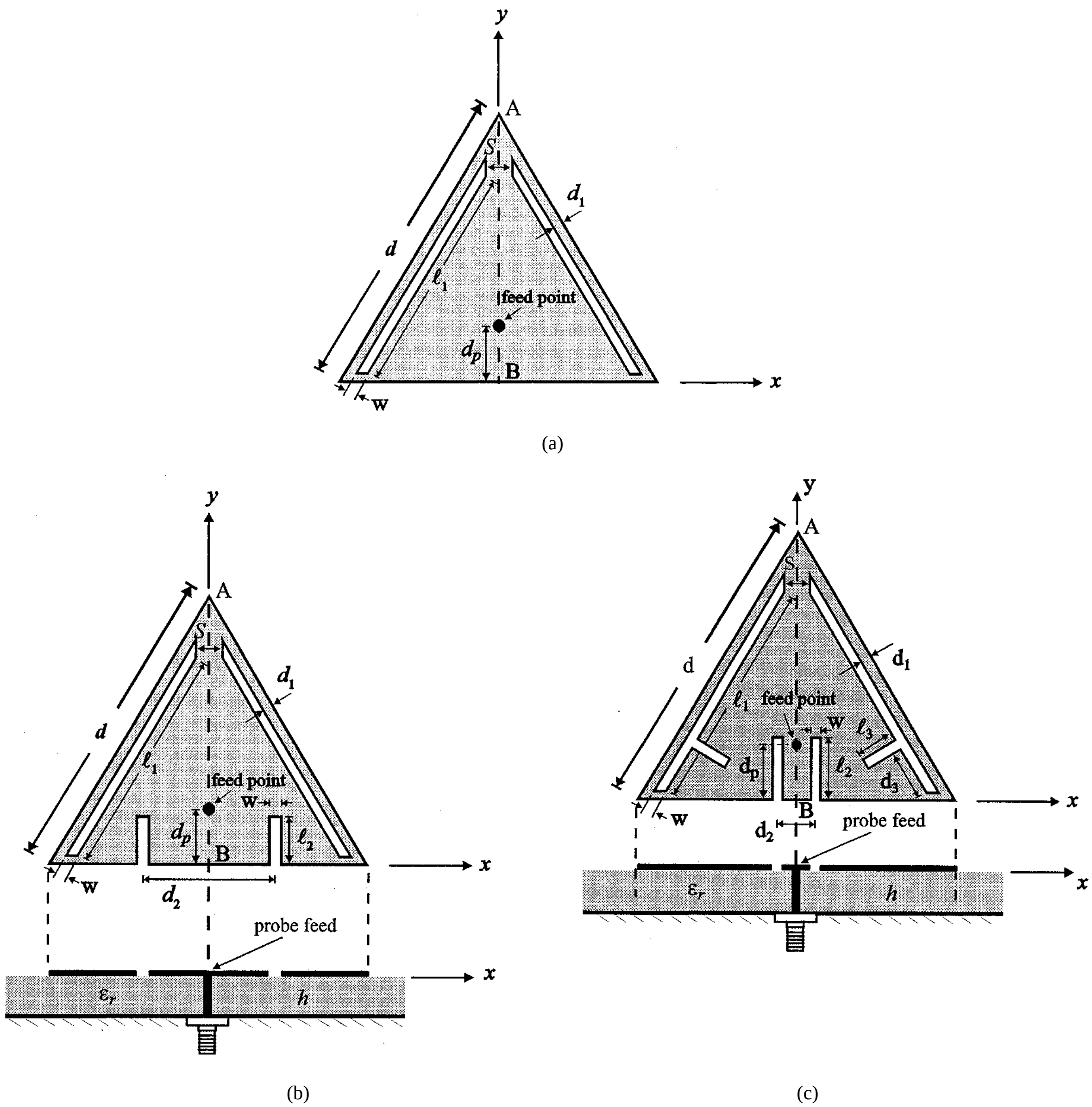
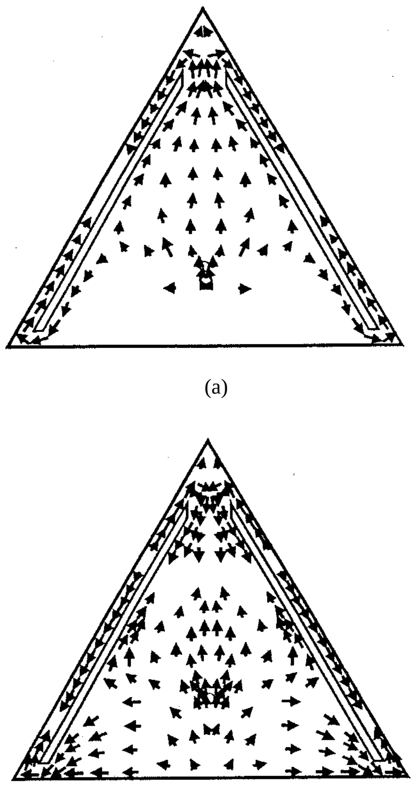


Fig. 1. (a) Geometry of the proposed simple slot-loaded equilateral-triangular microstrip antenna for dual-frequency operation. (b) Geometry of the proposed slot-loaded equilateral-triangular microstrip antenna for dual-frequency operation. (c) Geometry of the proposed slot-loaded equilateral-triangular microstrip antenna for broad-band operation.

side length of the patch, and the distance (d_1) between slot 1 and the side edge is chosen to be 1 mm $(<0.03d)$ in this study. Due to the presence of these slots, the fundamental resonant frequency (f_{10}) of the triangular patch is found to be slightly affected, because slot 1 is mainly in parallel to the excited patch surface current density of the TM_{10} mode and slot 2 is placed near the bottom edge of the patch, where the patch surface current distribution of the TM_{10} mode is relatively very weak (see the related simulated results shown in Section III-A). On the other hand, with the presence of slot 1, the surface current distribution of the TM_{20} mode is modified such that the small dip in the broadside direction of the radiation pattern [5] is removed. By inserting slot 2 at the bottom edge of the patch, the excited surface current paths of the TM_{20} modes are lengthened, which effectively lowers the resonant frequency f_{20} of the TM_{20} mode. This suggests that by varying the positions and lengths of slot 2, the frequency ratio of the two operating frequencies can be adjusted. A single probe feed for the excitation of the TM_{10} and TM_{20} modes can also be easily located along the center line $\overline{AB}$ of the patch in this design.

B. Broad-Band Design

The present design is to make the first two broadside-radiation modes (TM_{10} and TM_{20}) of the triangular patch [5] to be excited at frequencies close to each other to form a wider operating bandwidth. For this purpose, as referred to the antenna structure in Fig. 1(c), a pair of slots (denoted as slot 3 here) with dimensions $(\ell_3 \times w)$ is protruded from slot 1 at a distance d_3 away from the bottom edge of slot 1. When d_3 is selected to be less than 0.2 times the patch's side length d, the perturbation of slot 3 on the fundamental resonant frequency f_{10} can be greatly reduced, because in this case slot 3 will be in the region



(a)

(b)

Fig. 2. Simulated surface current distributions for the antenna shown in Fig. 1(a); $d = 50$ mm, $\varepsilon_r = 4.4$, $h = 1.6$ mm, $w = 1$ mm, $d_1 = 1$ mm, $S = 4.4$ mm, $\ell_1 = 40$ mm. (a) TM_{10} mode. (b) TM_{20} mode.

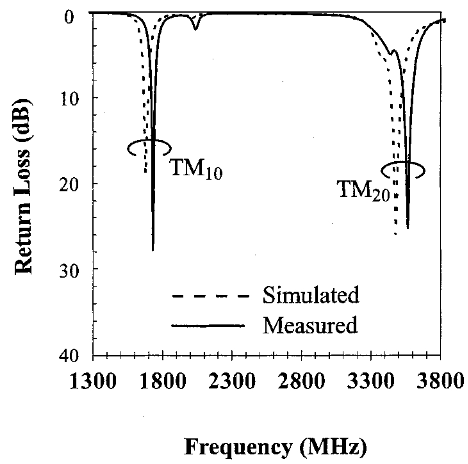


Fig. 3. Simulated and measured return loss of the TM_{10} and TM_{20} mode excitation of the antenna shown in Fig. 1(a); antenna parameters are the same as in Fig. 2.

near the bottom edge of the patch where the patch surface current distribution of the TM_{10} mode is relatively very weak. The arrangement and effect of slot 1 and slot 2 are the same as described in part A of this section.

On the other hand, it is expected that with the presence of slots 1, 2, and 3, the equivalent patch surface current path of the TM_{20} mode is strongly meandered and, thus, the resonant frequency f_{20} can be significantly lowered and occurred at a frequency close to f_{10}. It is also found that with the present proposed broad-band design, both resonant modes of TM_{10} and TM_{20} can easily be excited using a single probe feed at a position along the center line $\overline{AB}$ of the triangular patch, similar to the dual-frequency design (described in part A of this section).

III. Results and Discussion

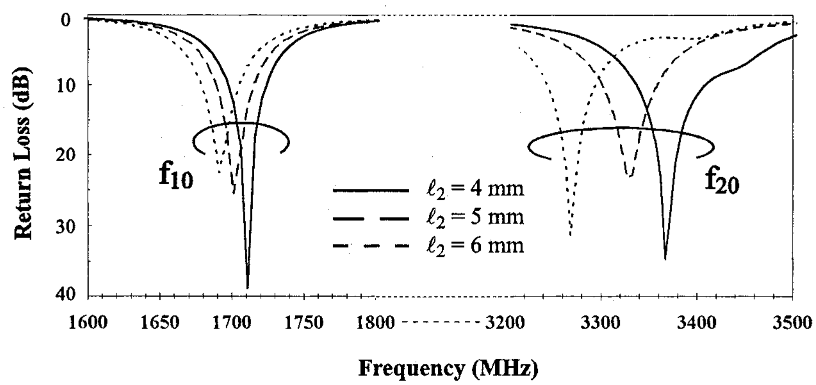
A. The Proposed Dual-Frequency Design

To begin with, simulated results obtained using IE3D™ [10] for the antenna design shown by Fig. 1(a) are first presented in Fig. 2 in which typical results of the excited patch surface current distributions of TM_{10} and TM_{20} modes are shown. It should first be noted that the loading of slot 1 has small effects on the TM_{10} mode and, on the other hand, can make the distribution of patch surface current density of TM_{20} mode more uniformly distributed in the center portion of the triangular patch to make the radiation patterns of the TM_{20} mode more close to that of the TM_{10} mode. It is also noted that although, in the simulation results, the excited patch surface currents are constrained to flow around the end of a slot, the measured gains of the two operating frequencies associated with the perturbed TM_{10} and TM_{20} modes are about the same as those of a corresponding unslotted antenna. It can also be observed that for the TM_{10} mode, the excited patch surface current is less distributed in the patch below the feed position, which suggests that the additional loading of slot 2 in Fig. 1(b) and slot 3 in Fig. 1(c) will have small effects on the effective patch surface current path of the TM_{10} mode and the resonant frequency f_{10} will be slightly affected. On the other hand, for the TM_{20} mode, it is seen that the excited patch surface current is strongly distributed near the bottom edge of the patch. This implies that the additional loading of slot 2 and slot 3, will result in a large perturbation of the effective patch surface current path of the TM_{20} mode, and the resonant frequency f_{20} can be significantly decreased, which makes both the dual-frequency operation with various frequency ratios and the broad-band operation possible. Fig. 3 also shows the simulated and experimental results of the return loss for the antenna design of Fig. 1(a). Results show satisfactory agreement for the present dual-frequency design of a simple slot-loaded triangular microstrip antenna, and a frequency ratio of about 2.06 is obtained (see Table I for the case of $d_2 = \ell_2 = 0$).

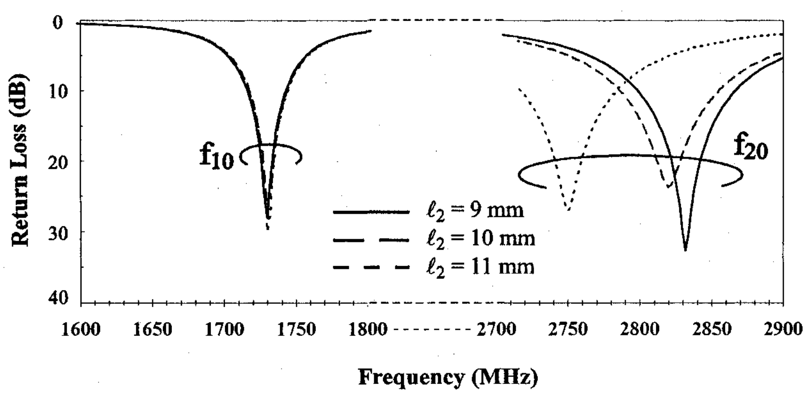
For the case of antenna design shown in Fig. 1(b), the effects of varying the positions and lengths of slot 2 are also studied. Fig. 4(a) and (b) shows typical measured return loss of TM_{10} and TM_{20} modes for the cases of $d_2 = 37.2$ mm and 10.8 mm. It is clearly seen that by increasing the length of slot 2, the resonant frequency f_{20} decreases much more quickly than f_{10}, which makes the frequency ratio (f_{20}/f_{10}) of the two frequencies decreased. The corresponding measured data are also listed in Table I for comparison. It is first seen that the optimal feed point in the present design is within 2 mm and is thus not sensitive to the variation in the length and position of slot 2. Also, it is found that due to the loading of slot 2, the frequency ratio decreases with decreasing distance d_2 and increasing slot length ℓ_2. A tunable frequency-ratio range of about 1.16–2.06

TABLE I
RESULTS OF THE PROPOSED DUAL-FREQUENCY TRIANGULAR MICROSTRIP ANTENNA WITH VARIOUS POSITIONS AND LENGTHS OF THE INSERTED SLOTS (SLOT 2) AT THE BOTTOM EDGE OF THE PATCH; ANTENNA PARAMETERS ARE GIVEN IN FIG. 2

d_2, ℓ_2 (mm)	d_P (mm)	f_{10} (MHz), BW (%)	f_{20} (MHz), BW (%)	f_{20}/f_{10}
0, 0	10.0	1731, 1.56	3565, 1.82	2.06
37.2, 4	11.0	1711, 1.52	3372, 2.05	1.97
37.2, 5	11.0	1701, 1.65	3327, 1.65	1.95
37.2, 6	11.0	1691, 1.66	3268, 1.53	1.93
25.0, 6	11.0	1720, 1.51	3123, 2.34	1.82
25.0, 7	11.0	1721, 1.74	3046, 2.10	1.77
25.0, 8	11.0	1721, 1.75	2967, 1.82	1.72
10.8, 9	10.5	1730, 1.39	2832, 2.44	1.64
10.8, 10	10.5	1730, 1.50	2820, 2.41	1.63
10.8, 11	10.5	1730, 1.56	2750, 2.40	1.59
4.0, 14.4	9.5	1754, 1.43	2036, 1.62	1.16



(a)



(b)

Fig. 4. Measured resonant frequencies, f_{10} and f_{20}, against frequency for the proposed antenna [Fig. 1(b)]; other parameters are the same as in Fig. 2. (a) $d_2 = 37.2$ mm. (b) $d_2 = 10.8$ mm.

is obtained for the proposed dual-frequency design. It should be noted that when ℓ_2 is larger than 14.4 mm $(\sim 0.29d)$ in this design, there is no point which gives a good matching condition for the two operating frequencies simultaneously. This be-

TABLE II
DESIGN AND PERFORMANCE OF THE PROPOSED BROADBAND TRIANGULAR MICROSTRIP ANTENNAS [FIG. 1(c)]; OTHER PARAMETERS ARE SHOWN IN FIG. 6. THE RESULTS FOR THE REFERENCE ANTENNAS ARE OBTAINED FOR THE CONVENTIONAL TRIANGULAR MICROSTRIP ANTENNAS [5] OPERATED IN THE TM_{10} MODE

	d (mm)	ℓ_1, d_1 (mm)	ℓ_2, d_2 (mm)	ℓ_3, d_3 (mm)	Bandwidth (10dB return loss)
Antenna B1	50	40, 1.0	14.7, 4.5	8.0, 8.5	1720-1799MHz (4.5%)
Reference B1	50	0, 0	0, 0	0, 0	1717-1743MHz (1.5%)
Antenna B2	40	30, 1.0	8.7, 3.6	7.4, 5.5	2200-2311MHz (4.9%)
Reference B2	40	0, 0	0, 0	0, 0	2160-2201MHz (1.9%)

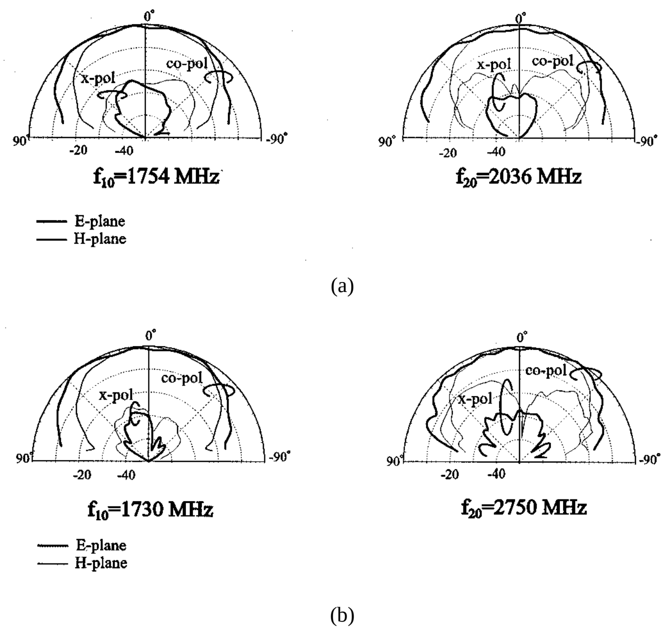


Fig. 5. Measured *E*-plane and *H*-plane radiation patterns for the proposed antenna [Fig. 1(b)]; other parameters are the same as in Fig. 2. (a) The design with $d_2 = 4.0$ mm, $\ell_2 = 14.4$ mm. (b) The design with $d_2 = 10.8$ mm, $\ell_2 = 11.0$ mm.

havior limits the present dual-frequency operation with a frequency ratio less than 1.16.

Typical measured radiation patterns at the two operating frequencies for the cases with $\ell_2 = 14.4$ mm, $d_2 = 4$ mm and $\ell_2 = 11$ mm, $d_2 = 10.8$ mm are also plotted in Fig. 5(a) and (b), respectively. It is observed that the two frequencies are of same polarization planes and have similar broadside radiation characteristics. Good cross-polarization (XP) radiation of the two frequencies are also obtained, especially for the lower operating frequency, f_{10}.

B. The Proposed Broad-Band Design

Based on the broad-band design shown in Fig. 1(c), two cases of the triangular patch sizes of $d = 50$ mm (antenna B1) and 40 mm (antenna B2) are implemented. Fig. 6 shows the measured return loss of antennas B1 and B2. It is clearly seen that for both cases, large operating bandwidths formed by the excitation of two adjacent resonant modes at 1734 and 1784 MHz for antenna B1 and 2218 and 2290 MHz for antenna B2 are observed. The

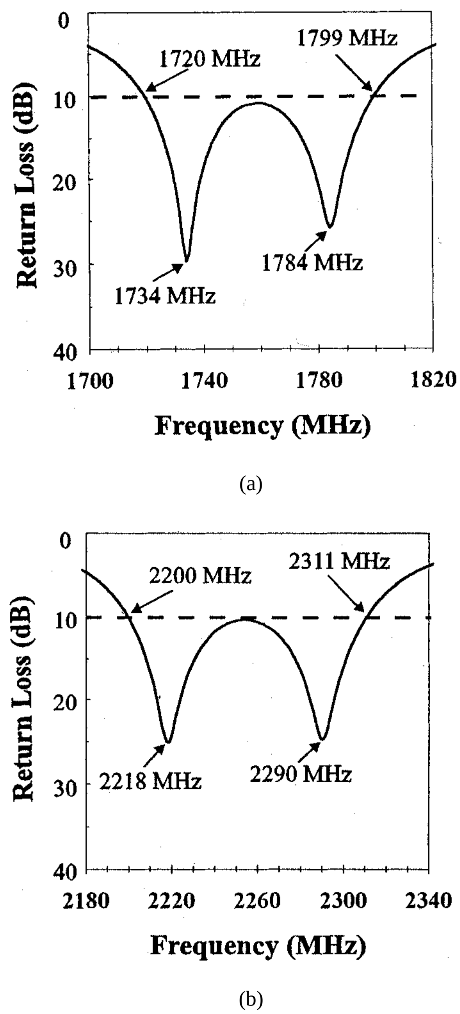


Fig. 6. Measured return loss for the proposed broad-band design shown in Fig. 1(c) with $\varepsilon_r = 4.4$, $h = 1.6$ mm, $w = 1$ mm, $d_1 = 1$ mm. (a) Antenna B1: $d = 50$ mm, $S = 4.4$ mm, $d_p = 13.9$ mm. (b) antenna B2: $d = 40$ mm, $S = 3.9$ mm, $d_p = 10.6$ mm. Parameters of the embedded slots in antennas B1 and B2 are listed in Table II.

corresponding parameters of the loading slots and the antenna performance are listed in Table II in which the performance of the conventional triangular microstrip antennas without slots (references B1 and B2) [5] in the TM_{10} mode is also shown for comparison. It is noted that the fundamental resonant frequencies of references 1 and 2 are, respectively, at 1730 MHz and

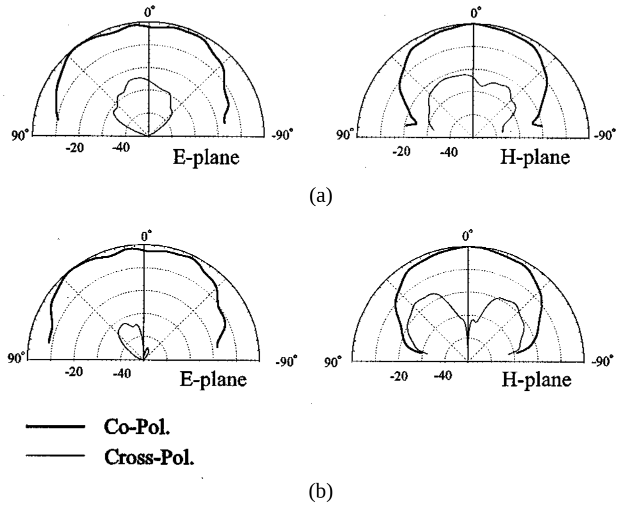


Fig. 7. Measured *E*-plane (y–z plane) and *H*-plane (x–z plane) radiation patterns for antenna B1 given in Fig. 6. (a) $f = 1734$ MHz. (b) $f = 1784$ MHz.

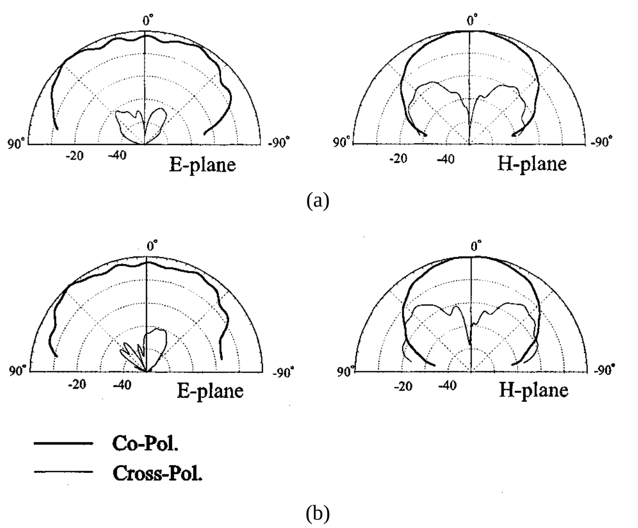


Fig. 8. Measured *E*-plane (y–z plane) and *H*-plane (x–z plane) radiation patterns for antenna B2 given in Fig. 6. (a) $f = 2218$ MHz. (b) $f = 2290$ MHz.

2180 MHz, which are close to the first resonant frequencies of antennas B1 and B2 studied here. This behavior verifies the prediction that the fundamental TM_{10} mode is slightly affected in the present design. Also, from the comparison of the patch surface current distributions (obtained using IE3D[1]) of the first two modes of the present design with those of the reference antennas in the TM_{10} and TM_{20} modes, the mode-excitation predictions described in Section II are also justified.

It is also seen that the antenna bandwidths, determined from 10-dB return loss, are 4.5% and 4.9% for antennas B1 and B2, respectively. These two operating bandwidths are, respectively, as large as 3.0 times that (1.5%) of reference B1 and 2.6 times that (1.9%) of reference B2. The radiation patterns at the two resonant modes of antennas B1 and B2 are also measured and plotted in Figs. 7 and 8, respectively. These two resonant modes are seen to be of same polarization planes and similar radiation characteristics.

[1]IE3D is a trademark of Zeland, Ltd.

IV. CONCLUSION

The novel slot-loaded equilateral-triangular microstrip antennas with dual-frequency and broad-band operations have been proposed and experimentally studied. The two operating frequencies of the proposed dual-frequency design are of same polarization planes and also have similar radiation characteristics. This design also shows a tunable range of about 1.16–2.06 for the frequency ratio of the two operating frequencies. The broad-band operation achieved by modifying the proposed dual-frequency design has also been successfully implemented. The antenna bandwidth of the proposed design reaches more than 2.6 times that of the conventional triangular microstrip antennas.

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