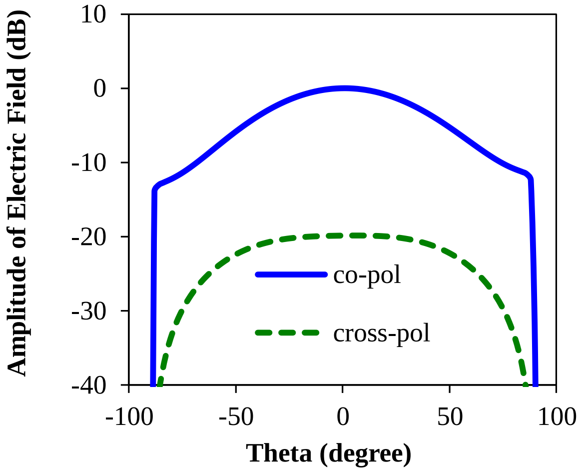
distributions. Secondary, in order to enhance the distraction, the originally rectangular metallic patch is modified to a triangular shape as shown in Figure 2, so that the disturbance on the electric field will become much more than ever. Since the resonant frequencies of the two modes in this antenna can be altered much easily so that the separation variation of frequencies becomes possible. After the investigation on disturbing shape, two rectangular metallic strips are placed vertically within an antenna cavity as indicated in Figure 3. Since there are three layers of substrates, the disturbing of the electric field can be done at higher and lower levels. Therefore, more modes can be excited from the original TM01 mode, and radiations will still remain acceptable with this arrangement. Furthermore, the investigation is also on the case of disturbing patch with a concaved structure, such as the one with one concave in Figure 4, with two concaves in Figure 5, and with five concaves in Figure 6. In order to prove the design concept, the results from ENSEMBLE and HFSS simulation tool are provided. In addition, experimental data is used to reconfirm the validity. During the experiment, there are various substrates used, such as Duroid 5880, 4003, FR-4 and air in order to meet the demand of a microstrip antenna with multiple layers. Notice that the substrate of air in experiments is made with a small piece of suspended layer, and this technique is indicated in [15].

3. Results and Comparisons

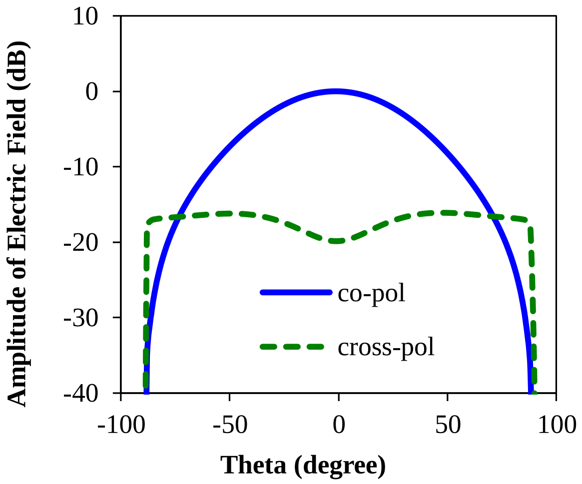
For the antenna with a single disturbing patch in Figure 1, the return loss shows that the resonant frequencies of the lower mode obtained from ENSEMBLE and HFSS are 3.51 and 3.50 GHz, respectively. The higher mode resonates at 4.91 and 4.75 GHz. The frequency differences are within an acceptable range, and the lower-enough return loss shows that these two modes are well matched. Figure 7 demonstrates the simulated electric field along cross section of the cavity. Near the surrounding of disturbing metal, the higher and lower modes have different distributions. This phenomenon due to metallic disturbing reflects the expectation from design concept. Figure 8 shows the radiation pattern of the lower mode. On the major planes, the co-polarization radiation pattern shows an acceptable single beam, and the cross-polarization one is lower enough. For higher mode, the radiation patterns in Figure 9 demonstrate that the patterns of co-polarization fields are also acceptable on both two major planes, and those of cross-polarization is far below co-polarization's. Table 1 shows the resonant frequencies of two modes obtained from experiment, ENSEMBLE and HFSS. The error is only as low as 3%, which may be due to the fringe effect because the data from ENSEMBLE is simulated with an infinite ground. As studied [16], the difference of these resonant frequencies is so limited that similar radiations from experiments should be expected; therefore, they are not presented here for comparison. Since data from two simulations are so close, it proves that the concept of an antenna with a single disturbing patch does work at dual bands. According to the comparisons earlier, it is sure that the simulation tools are eligible for this kind antenna structure with disturbing patches. For the antenna with a triangular patch in Figure 2, the return loss shows that this antenna resonates at 4.36 and 5.1 GHz and the impedance matching for these two modes are only slightly different. These two frequencies are not too far from those of the antenna in Figure 1. Table 2 shows the comparisons of resonant frequency between these two antennas with different disturbing shapes. Notice that the frequency separation offered from the triangular patch is much larger than that from the rectangular one. Note that the computation of the band separation is based on the following formula:

$$\Delta = \frac{B\left(f_2 - f_1\right) - A\left(f_2 - f_1\right)}{A\left(f_2 - f_1\right)}$$

Apparently, a disturbing shape of the metal can be used to adjust frequency separation of two modes for this kind of antenna. Figures 10 and 11 show the radiation of the excited two modes, and the results of co- and cross-polarization are still acceptable. For the antenna with two disturbing patches placed vertically, the results of return loss from ENSEMBLE and HFSS both demonstrate that three individual modes are created at around 1.84, 2.02 and 2.3GHz. The simulated resonant frequencies are slightly different from those from experiments; the difference could be due to the fabrication error. Only the measured second mode resonates slightly from the simulation, the remaining frequencies are pretty close. In order to confirm the design concept, electric field distributions of these three different modes are shown in Figure 12. It shows the electric field distribution of these three modes; that means the vertically disturbing patches do work as expected. Apparently, their distributions are all different with each other so that their resonant frequencies also vary. Since the simulation for radiation patterns from ENSEMBLE has been already verified by HFSS, so only the ENSEMBLE data is shown later on. Figures 13-15 depict the simulated radiation patterns of these three modes; all of the single beam and lower cross-polarization radiation prove that the radiations are well acceptable. It is clear that the design of disturbing patches placed vertically makes tri-band operation possible for antennas. For those antennas with concaved disturbing patches, the result of return loss shows that it resonant at 1.411 and 2.379GHz. The radiation patterns in Figures 16 and 17 prove that these results are with acceptable range. The return loss reveals that the resonant frequencies of the

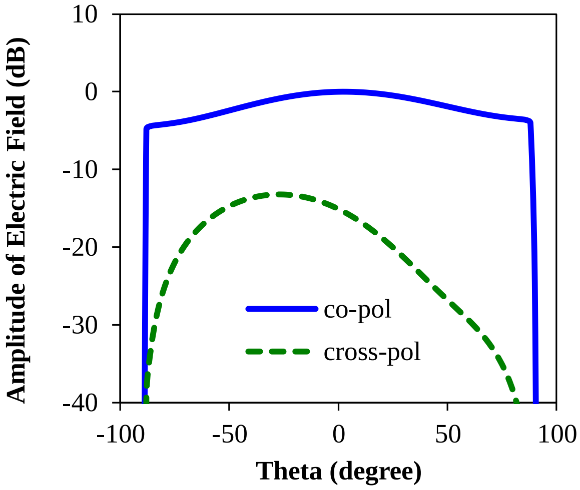


(a)

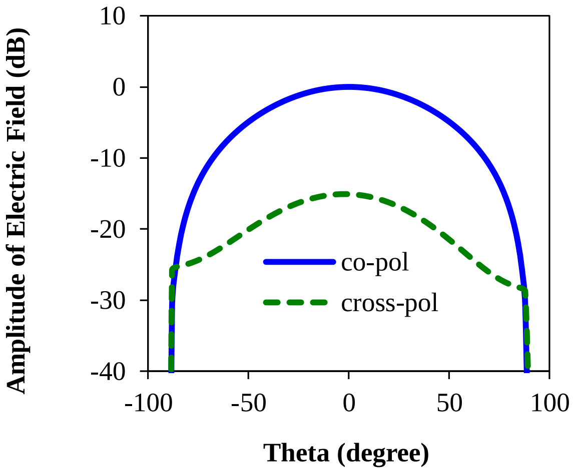


(b)

Figure 17: For the second mode of the antenna in Figure 4, the simulated radiation patterns on different planes obtained from ENSEMBLE: (a) E-plane, (b) H-plane. The structure dimensions are the same as those in Figure 16, the resonant frequency is 2.379GHz.

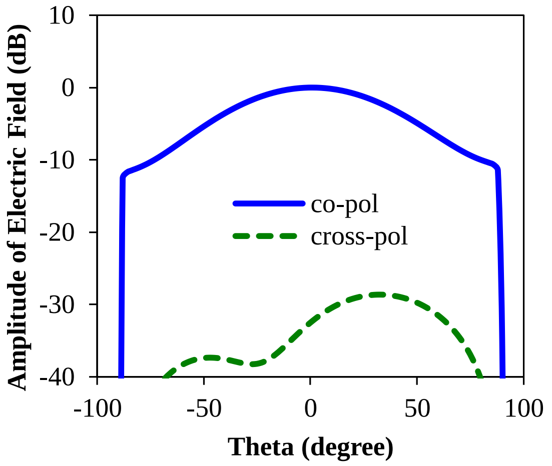


(a)

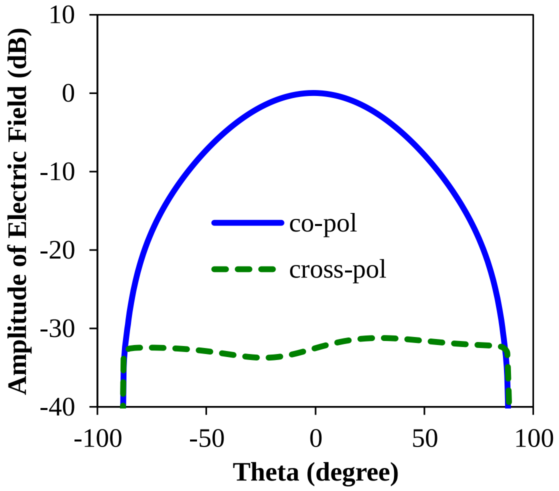


(b)

Figure 18: For the first mode of the antenna in Figure 5, the simulated radiation patterns on different planes obtained from ENSEMBLE: (a) E-plane, (b) H-plane. The structure dimensions are: L_x=8cm, L_y=5cm, w_1=1.125cm, w_2=0.375cm, w_3=2.5cm, w_4=1.25cm, s_1=5.5cm, s_2=1.4cm, the resonant frequency is 1.41GHz.

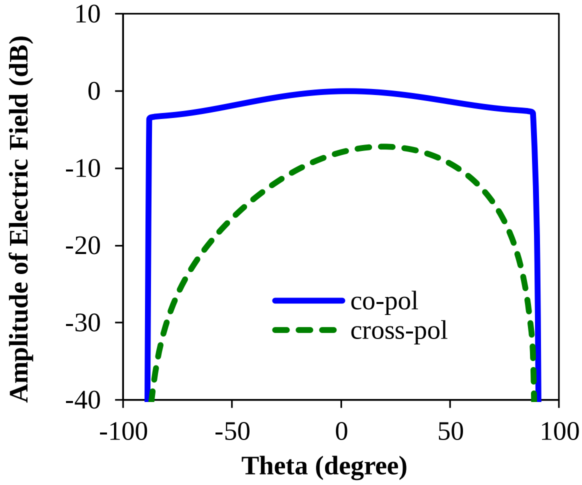


(a)

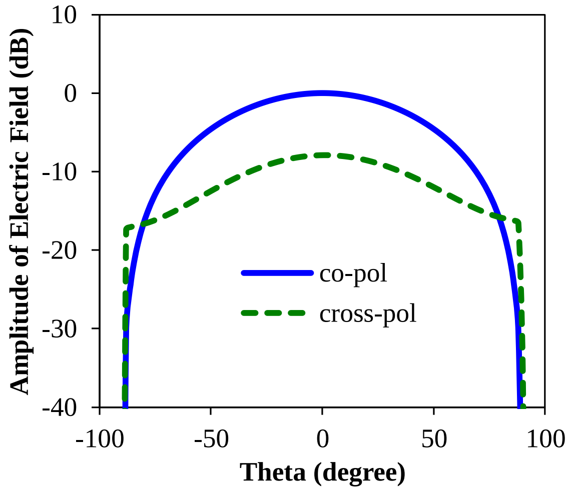


(b)

Figure 19: **For the second mode of the antenna in Figure 5, the simulated radiation patterns on different planes obtained from ENSEMBLE: (a) E-plane, (b) H-plane. The structure dimensions are the same as those in Figure 18, the resonant frequency is 2.42GHz.**

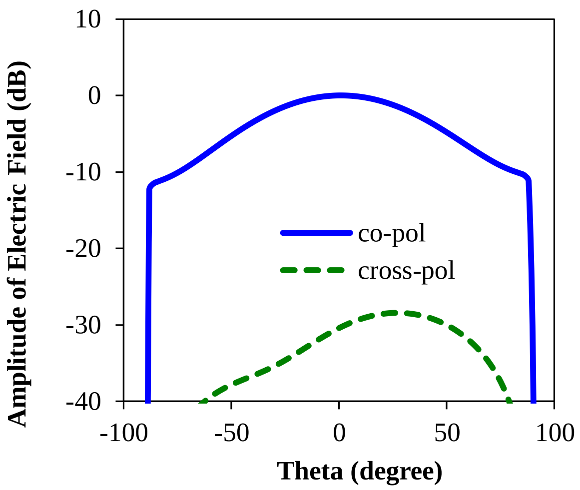


(a)

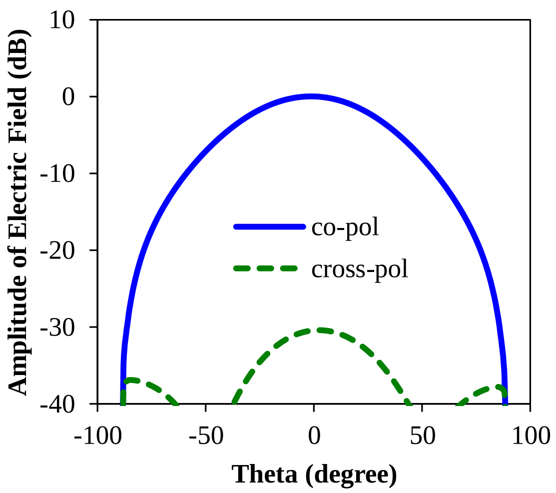


(b)

Figure 20: **For the first mode of the antenna in Figure 6, the simulated radiation patterns on different planes obtained from ENSEMBLE: (a) E-plane, (b) H-plane. The structure dimensions are: L_x=8cm, L_y=5cm, w_1=1.125cm, w_2=0.375cm, w_3=1cm, w_4=0.5cm, s_1=5.9cm, s_2=1.4cm, the resonant frequency is 1.32GHz.**



(a)



(b)

Figure 21: For the second mode of the antenna in Figure 6, the simulated radiation patterns on different planes obtained from ENSEMBLE: (a) E-plane, (b) H-plane. The structure dimensions are the same as those in Figure 20, the resonant frequency is 2.4GH

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