simulations based on the MoM, Ensemble v.5.1, and measurements. Finally, this model has been applied to the synthesis of two antennas presented in [19, 20] and very accurate results have been obtained.

REFERENCES


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4. RADIATION DEGRADATION FROM PIFA WITH REDUCED AIR GAP

The resonant frequency $f_r$ of the PIFA over its size can be approximated by [9]:

$$f_r = \frac{c}{4\alpha(l + w)}.$$  (1)

where $c$ is the speed of light, $l$ and $w$ are the length and width of the PIFA element, respectively, and $\alpha$ is a constant of about 0.9.

It is noted that the PIFA radiation and impedance bandwidth are dependent on the separation distance between the radiator and the ground. Generally, the higher the air gap (separation between the PIFA and the ground) is, the greater the obtainable bandwidth and gain can be achieved. However, there is an increasing need for further reducing the PIFA size, in particular, the air-gap distance, in order to make the mobile phone thinner. Figure 3 shows the differences of radiation pattern between the conventional PIFA and the PIFA with a reduced air gap. The conventional PIFA shows considerable backward radiation due to the small ground plane. Such unwanted backward radiation becomes even stronger when the antenna is brought closer to the ground plane, since as more surface waves are excited and radiate from the edges and corners.

3. EBG-PIFA ANTENNA DESIGN

It can be seen from Figure 1 that conventional PIFAs have the limitations of a restricted band operation and a reduction in the radiation efficiency due to the losses caused by backward radiation. Furthermore, PIFA size reduction can lead to decreases in bandwidth and gain. In this section, we will demonstrate that PIFA performance degradation can be mitigated by applying an EBG substrate in order to replace the conventional conductive ground.
EBG structures are capable of controlling the flow of electromagnetic waves. Within the EBG structure, there is a range of frequencies where propagating modes can be fully or partially suppressed in one or more dimensions. This range of frequencies is known as the electromagnetic stopband, or bandgap [10]. Due to these properties, EBGs can provide significant advantages for suppressing and directing radiation, and thus improving efficiency when used in antennas. Compared to other EBG structures, the mushroomlike EBG structure has the highly desired feature of compactness, which is important in communications applications. Its bandgap features are revealed in two ways: (i) the suppression of surface-wave propagation and (ii) the in-phase reflection coefficient. The feature of surface-wave suppression helps to improve antenna performance, for example, by increasing antenna gain and reducing backward radiation [11]; while the in-phase reflection feature leads to low-profile antenna design [12].

Generally, for a planar EBG structure, the centre frequency of the stopband is determined from $f_0 = c/2S$, where $c$ is the speed of light in free space, and $S$ is the period of structure. For the mushroomlike EBG structure, it consists of four parts: metallic patches, connecting pins, a dielectric substrate, and a ground plane. This structure introduces an inductor $L$, which results from the current flowing through the vias, and a capacitor $C$, which is due to the gap effect between adjacent patches. For the structure [Fig. 2(a)] with patch width $W$, gap width $g$, substrate thickness $h$, and dielectric constant $\varepsilon_r$, the values of inductor $L$ and capacitor $C$ can be approximated by the following formulas [3],

$$L = \mu_0 h,$$  \hspace{1cm} (2)

$$C = \frac{W\varepsilon_r (1 + \varepsilon_r)}{\pi} \cosh \left( \frac{2W + g}{g} \right),$$ \hspace{1cm} (3)

where $\mu_0$ is the permeability of free space and $\varepsilon_0$ is the permittivity of free space. Thus, the bandgap can be determined by

$$\omega = \frac{1}{\sqrt{LC}},$$ \hspace{1cm} (4)

$$BW = \frac{\Delta \omega}{\omega} = \frac{1}{\eta} \sqrt{\frac{L}{C}},$$ \hspace{1cm} (5)

where $\eta$ is the free-space impedance ($\eta = 120\pi$).

However, the formulas only give an approximation of the resonant frequencies, since the effects from metallic vias in the EBG design are not considered. An accurate but complex model using the theory of transmission lines and periodic circuits can be found in [13].

The proposed EBG structure is simulated using the Ansoft HFSS™ 9.0 software. The dimensions are chosen as shown in Figure 2(a): square patches: $9 \times 9$ mm$^2$, patch gaps: 1.5 mm, ground plane: $46.5 \times 67.5$ mm$^2$, dielectric constant (EBG substrate): 9.8, and thickness: 1.905 mm. In theory, a broader bandgap results in a better control of the backward radiation of the antenna; thus, it is essential to put more elements onto the limited mobile-phone ground plane. In total, there are 24 ($4 \times 6$) elements in the proposed structure, which gives a frequency bandgap from 2.1 to 2.6 GHz [Fig. 2(b)]. Other structures with different numbers of

![Figure 5](image_url) Simulated and measured return losses ($S_{11}$) of a conventional PIFA and an EBG-PIFA. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

![Figure 6](image_url) Comparison between the measured radiation patterns of a conventional PIFA and an EBG-PIFA. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]
elements \((4 \times 4, 6 \times 6, \text{ and } 8 \times 8)\) have also been simulated, as shown in Figure 2(b). It can be seen that the bandgap region does not shift significantly as the period of structure remains unchanged.

The radiator size of both conventional PIFAs and EBG-PIFAs is \(8.4 \times 22.8 \text{ mm}^2\), which is made from a 1-mm-thick copper film with a conductivity of \(58.13 \times 10^6 \text{ S/m}\). Two shorting pins are used instead of a shorting strip at one edge of the radiator due to the ease of fabrication. The shorting pins connect the radiator and ground plane through the gap of EBG patches without touching them.

5. CONCLUSION

The radiation properties of planar inverted-F antennas (PIFAs) on electromagnetic bandgap (EBG) substrate have been presented. It was verified experimentally that the EBG structure (even with only \(4 \times 6\) elements) reduces surface waves, thus leading to an increase in directivity, bandwidth, forward and backward radiation ratios, and efficiency.

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