

Bandwidth Broadening in 2-D Dielectric Photonic Crystals Leaky-Wave Antennas

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Abstract

This paper investigates the use of multiple resonances to enhance the operational bandwidth of one-dimensional (1-D) leaky-wave antennas (LWAs) based on two-dimensional (2-D) photonic crystals (PCs). As is well known, the electromagnetic response of PCs is strongly dependent on the geometrical and material properties of their constituent elements. In this work, the lattice constant p and the cylinder radii r_i , $i = 1, 2$, are tailored to engineer the properties of the two PC slabs, enabling the generation of closely spaced resonances. By a proper position of the source, a simultaneous excitation of these resonances is achieved, resulting in a significant bandwidth enhancement. A comparative analysis between uniform and multi-slab configuration is finally presented, providing useful design guidelines for wideband 1-D lattice LWAs.

1 Introduction

Focused electromagnetic emission from sources embedded in two-dimensional (2-D) photonic crystals (PCs) [1] has been explored in lattices composed of dielectric cylinders in air or circular voids in a dielectric media [2], [3]. In particular, in [2] a detailed analysis of the radiation mechanisms of 1-D transversely open waveguides (OWs) based on 2-D dielectric lattices has been carried out by adopting a leaky-mode interpretation. The study combined the analysis of Bloch-mode band diagrams of 2-D PC structures with the investigation of bound and radiative modes in OW, providing an effective framework for antenna analysis. Furthermore, it was demonstrated that an OW formed by stacking of a finite number of periodic chains of circular dielectric cylinders behaves as a LWA [4], owing to the propagation of a dominant leaky air mode (AM) capable of radiating a narrow beam at broadside. Also, the typical scanning with frequency is observed, with a beam pointing at higher θ angles (see Fig. 1) when the frequency is increased. This framework allows for a design of an antenna prototype in the K-band, subsequently validated through experimental measurements, obtaining good agreement with the theoretical predictions, thereby confirming the effectiveness of the proposed model [5]. Despite their promising radiative properties, antennas based on resonance phenomena typically suffer from a relatively narrow operational bandwidth,

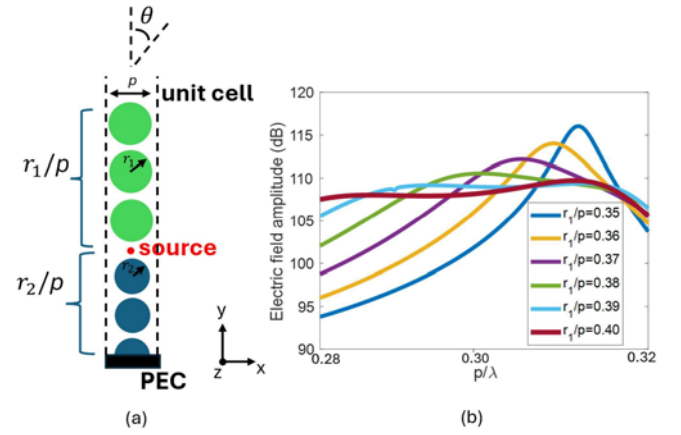


Figure 1. (a) Schematic view of the unit cell of the 2-D structure composed by two different Photonic Crystal (PC) layers. The dielectric parameters of the cylinders are: $\epsilon_r = 7.9$ and $\text{tg}\delta = 0.0006$. (b) Electric field amplitude measured at the probe, located at the source position, using the principle of reciprocity [10], as the ratio r_1/p varies at the fixed $r_2/p = 0.35$.

which limits their practical applicability and poses several constraints for the materials dispersion and parameters sensitivity. Other researchers have been focusing on widening the bandwidth of resonant [6, 7] and Fabry-Perot cavity antennas (FPCAs) [8, 9] by adding a number of additional layers to the antenna superstrates. In particular, in [8] an approach based on a homogenized leaky mode explained the bandwidth enhancement in terms of a $\beta \simeq \alpha$ condition extended in a wide frequency band. More recently, the effect of multiple leaky resonances, each associated with a different layer, has been clearly assessed as a mechanism for bandwidth broadening [9].

In this contribution, we present a preliminary study aimed at enhancing the operational bandwidth of such 1-D lattice LWAs. By employing two slightly different PC layers, two closely spaced resonances can be effectively combined through a careful source positioning, leading to a substantial widening of the operational band. Comparison with conventional uniform lattices highlights the advantages of the proposed non-uniform configuration, providing practical guidelines for the design of a broadband lattice LWA.

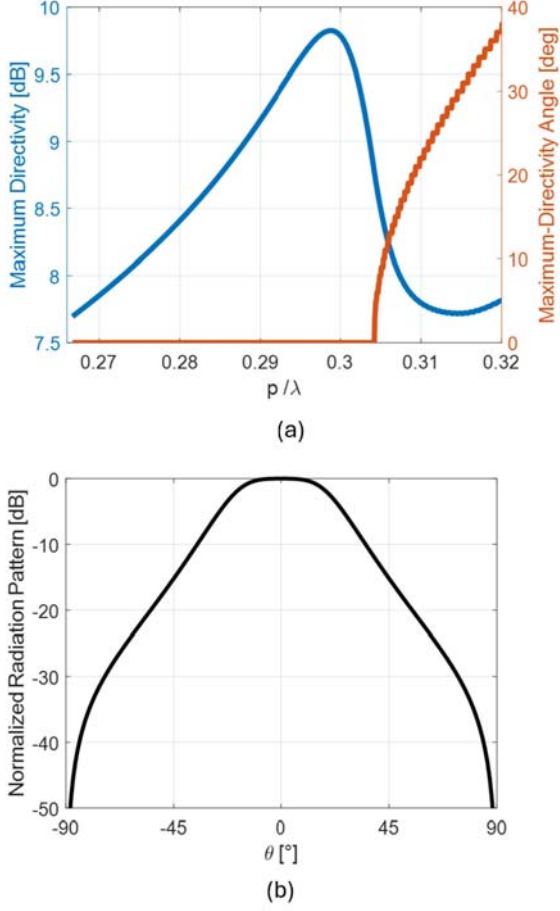


Figure 2. (a) Plot of maximum directivity and maximum directivity angle as a function of the normalized frequency p/λ for the infinite structure ($r_1/p = 0.37$, $r_2/p = 0.35$). (b) Normalized radiation pattern at broadside ($p/\lambda = 0.299$).

2 Design methodology for bandwidth enhancement

Schematic view of the unit cell for the proposed configuration is shown in Fig. 1(a). The structure is composed of two layers of multiple, axes-aligned dielectric rods, so that two different PC slabs are observed. In the first slab, the three green cylinders are characterized by a given r_1/p , with r_1 being the cylinder radius and p the lattice period, whereas in the second slab, positioned close to the ground plane, another ratio r_2/p is employed and the last blue cylinder is bisected in its center. The dielectric properties of the cylindrical rods are $\epsilon_r = 7.9$ and $\text{tg}\delta = 0.0006$. Based on the modal field configurations analyzed in [3], where a uniform PC is evaluated, the unit cell of the OW is chosen by bisecting with a ground plane the central rod. This allows for obtaining high directivity by exciting the dominant (zero th-order) leaky air mode AM_0 . Moreover, in the non-uniform case, the proposed approach exploits OW's multiple resonances, each pertaining to one PC layer. The simultaneous excitation of both resonances, which has been shown in similar LWAs [9] to be related to distinct leaky modes, is crucial for

improving the bandwidth performances. In the proposed non-uniform PC the source is placed at the two-layer interface, as indicated in Fig.1(a). This enables the excitation of both resonant modes, which results in an enhanced operational bandwidth, as it is illustrated for different values of the ratio r_1/p in Fig. 1(b). The value r_2/p is fixed and equal to 0.35. It is possible to observe that increasing the value of r_1/p leads to the appearance of two distinct peaks, which become clearly visible for $r_1/p = 0.39$. The two peaks gradually merge, forming a single resonance at approximately $r_1/p = 0.37$. Figure 2(a) shows the maximum directivity and the maximum directivity angle as a function of the normalized frequency for the infinite structure with $r_1/p = 0.37$ and $r_2/p = 0.35$. At broadside frequency ($p/\lambda = 0.299$) the directivity is $D = 9.8$ dB. Figure 2(b) shows the normalized radiation pattern at broadside obtained using reciprocity with CST Studio Suite [11]. In the uniform case, i.e., where all dielectric cylinders are identical, the structure exhibits a broadside directivity of 11.7 dB.

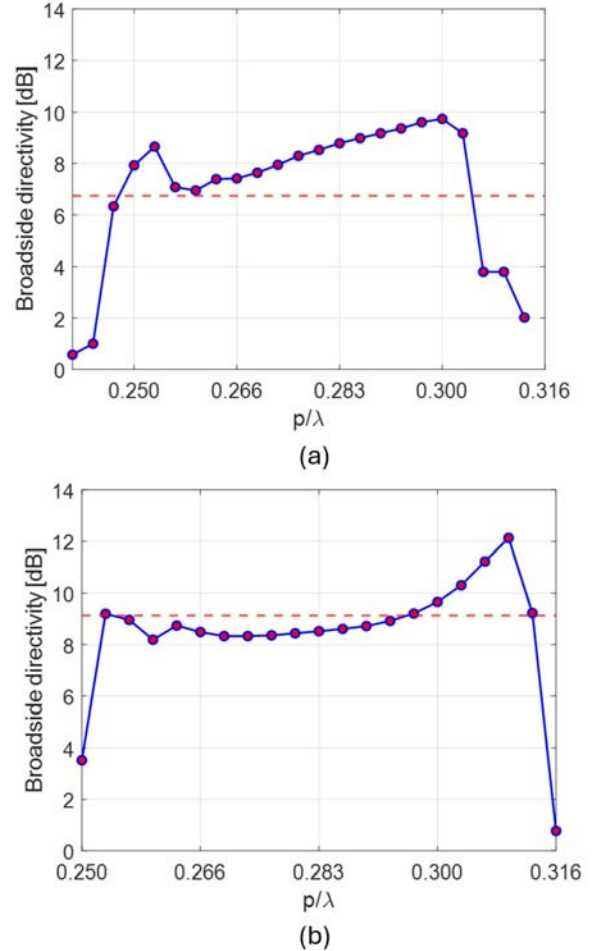


Figure 3. Broadside directivity as a function of normalized frequency for the truncated structures: (a) $r_1/p = 0.37$ and $r_2/p = 0.35$, $N_x = 13$; (b) $r_1/p = r_2/p = 0.35$, $N_x = 11$.

To accurately quantify the bandwidth improvement, the structure is truncated along the x -direction ($N_x = 13$) and its performance is compared with the uniform configura-

tion. The truncation number is chosen based on parametric studies. Figure 3(a) shows the broadside directivity as a function of the normalized frequency. A maximum broadside directivity of $D = 9.74$ dB is observed at $p/\lambda = 0.3$. A -3 dB fractional bandwidth of 20.7% is achieved. Figure 3(b) shows the broadside directivity as a function of the normalized frequency for the uniform case, in which all cylinders have the same dimensions. In this case, the truncation ($N_x = 11$) is determined by the attenuation constant of the dominant leaky mode [2]. The maximum directivity is slightly higher and reaches $D = 12.13$ dB at $p/\lambda = 0.310$. However, a significant reduction of the fractional -3 dB bandwidth is observed, reaching a value of 5.7%.

3 Conclusions

The results demonstrate that a significant bandwidth enhancement can be achieved by exploiting the partial overlap of closely spaced resonant modes supported by two slightly different photonic crystal layers, each made by stacks of infinite array of dielectric cylinders. Compared to the uniform configuration, the proposed design achieves a substantial increase in the operational bandwidth and guidelines are illustrated for the development of a broadband 1-D dielectric lattice leaky-wave antenna. Details on the leaky-wave modal analysis of the proposed configuration, along with additional results, will be presented at the conference.

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