Electromagnetic beaming from omnidirectional sources by inverse design

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Highly directional electromagnetic sources are desirable in a variety of fields and applications. By embedding point sources inside periodic lattices, radiation can be enhanced and confined within a small angular range. However, this directional source is far from perfect. Here, the authors demonstrate that by means of inverse design (ID) the periodic lattice can be modified to further enhance the radiation in a unique spatial direction. Experiments in the microwave regime show that with the ID structure the harvested radiation intensity is almost 60 times higher than for the isolated source and is confined within a 7.5° full width at half maximum angular range. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2838324]

By controlling the radiation properties of isotropic emitters through modification of the physical environment, attractive applications in diverse fields of optics are found. For instance, by using periodic dielectric structures (i.e., photonic crystals) it becomes possible to suppress or enhance the electromagnetic (EM) emission of a point source embedded inside the periodic structure.[1,2] For most applications, it is mandatory not only to enhance the emission efficiency but also to collimate the emitted EM radiation within a very small angular region. It has been demonstrated that photonic crystals (PhCs) can overcome those constraints and experiments have been performed on microwave radiation from monopole sources embedded in three-dimensional or two-dimensional (2D) PhCs.[3,4] However, there are two main drawbacks that strongly limit their use as enhanced highly directional radiation sources. Firstly, owing to the periodicity of the PhC, the directional emission comes from the photonic band structure, hence several highly directional beams will be generated depending on the symmetry of the lattice.[4] In addition, directional radiation occurs near the band edges, where the group velocity is small. Therefore, strong reflections can be expected at the interface, limiting the performance of the source due to the huge impedance mismatch between the PhC and free space.

Recently, a completely different strategy based on the optimization by inverse design (ID) of the dielectric structures able to perform a specific functionality task has been proposed[5] and applied to the design of EM devices of interest.[6–8] In this letter, we address the design and realization of an optimized enhanced highly directional source. We present experimental results in the microwave regime showing that a monopole antenna embedded in an inversely designed 2D dielectric structure made of alumina rods (see Fig. 1) shows enhancement and high directionality of its radiation along a prefixed direction. Our measurements demonstrate that the optimized device outperforms its analogous counterpart based on a 2D PhC, whose characterization is also shown here. Particularly, our proposed device generates a highly collimated beam with the radiation intensity along the forward direction being almost 60 times higher than that obtained with the isolated point source in free space, whereas its angular range of confinement is only 7.5°. Moreover, the ratio between forward and backward radiation is larger than 25 dB. In comparison, the corresponding device based on a 2D PhC produces a collimated beam that is 4 dB less intense and does not allow for radiation suppression in the backward direction.

Let us start with the case of a point source embedded in a 2D PhC. Enhanced directional emission can be achieved at frequencies close to a band edge and for which equifrequency contours become rounded. In such frequency regime, group velocity will become very low and the PhC will be-

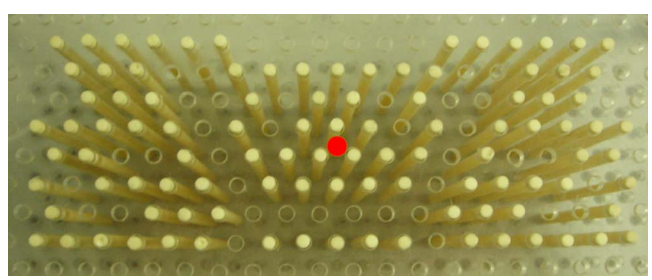

FIG. 1. (Color online) Photograph (taken from the top) of the cluster made of alumina rods that has been inversely designed to get a highly directional EM beam from a monopole antenna placed at the central cavity, whose position is highlighted by the red circle.

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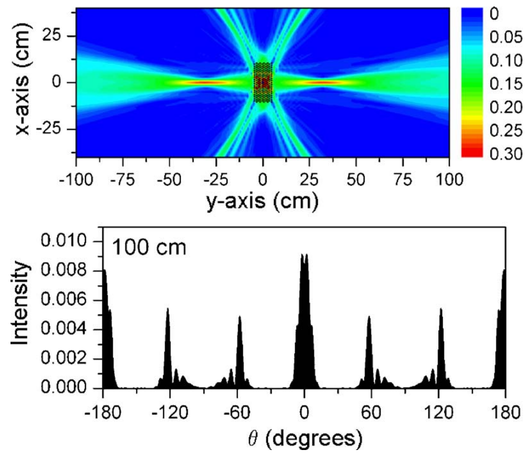

FIG. 2. (Color online) Performance of the directional source based on a PhC at a frequency of 24.33 GHz: (upper panel) map of the field amplitude emitted by a point source located at the slab center; (lower panel) angular dependence at 1 m from the center of the device. Simulations based on multiple scattering.

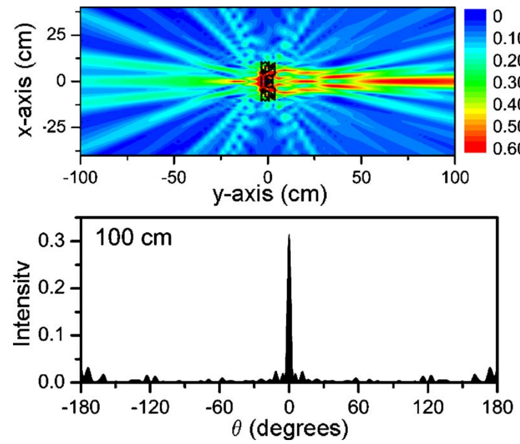

FIG. 3. (Color online) Performance of the directional source based on ID: (upper panel) map of the field intensity emitted by a point source embedded in the ID structure shown in Fig. 1; (lower panel) angular dependence at 1 m from the center of the device. Simulations based on multiple scattering.

have as an effective medium which can be described by a refractive index with modulus $\ll 1$.[9] Radiation emitted by the source will couple to the PhC mode and will exit the PhC well confined inside a small angular region.[3,4] The output beam will be divergent (convergent) if the effective index displayed by the PhC is positive (negative) but still maintaining its high directionality. Let us consider a specific case: a 2D PhC formed by a hexagonal array (lattice constant $a=1.153$ cm) of cylindrical alumina rods (radius $r=0.4$ cm, $\varepsilon=11$). Near the upper edge of the fifth photonic band for TM polarization (interval between 21.5 and 24.5 GHz), the previously explained conditions are accomplished,[9,10] so if a point source is embedded inside the structure, highly directional emission is expected. Figure 2 shows the amplitude of the electric field obtained when the source is placed inside the 2D PhC as well the intensity angular pattern at 1 m from the center of the device obtained by means of multiple-scattering simulations. Angle θ is defined as $\theta=\arctan(y/x)$. The frequency of the source is 24.33 GHz, which is in the fifth band (refractive index about -0.1).[10] At this frequency, we obtained an intensity maximum with our numerical method. The position of the source inside the PhC is properly selected to achieve a maximum enhancement of radiation. It can be seen that radiation is highly directional but it is emitted both forward and backward. Four additional beams are observed. This can be explained by considering that the PhC does not behave as a truly effective medium. Radiation is only allowed along the ΓM direction since for this direction the source and the mode are symmetry matched, whereas the PhC mode with wave vectors along ΓK displays an odd symmetry, which avoids its excitation. Thus, six beams are generated, two of them being the main forward and backward highly directional beams. Although backward radiation can be suppressed by used of a reflecting surface (a metal or a PhC with a band gap for the emitting frequency), the other generated beams are more difficult to control due to their more complex symmetry. Thus, other mechanisms to improve the directional emission from the source are needed.

A powerful choice to improve the performance is to use ID.[5–8] By means of a genetic algorithm, some of the rods forming the periodic structure are properly removed in order to maximize the intensity at a far-field point in the forward direction. ID was implemented to optimize the device performance (maximum field intensity at $\theta=0°$) at 23.35 GHz, which is within the frequency regime for which the PhC displays the beaming behavior. It should be mentioned that other frequencies within the fifth photonic band could have been selected for ID. Figure 1 shows the prototype built by using circular shaped alumina bars with the parameters previously mentioned. The position of the point source is highlighted in Fig. 1. Figure 3 is directly comparable with Fig. 2, but corresponding to the alumina bars placed in the aperiodic pattern shown in Fig. 1. It can be observed that an enhanced directional beam is emitted in the forward direction. In the far field, radiation in other undesired directions is highly suppressed, which confirms the improvement with respect to the periodic PhC structure. We have estimated the radiation efficiency of the proposed sources by calculating some parameters characterizing this kind of devices. Thus, the total energy radiated along all directions, γ, is a good estimation of the radiation behavior of the directional sources. The radiation of the narrow angular region [$\theta=0°$ in Figs. 2 and 3] relative to the whole radiation energy defines the parameter

TABLE I. Radiation properties of proposed directional sources: one based on a PhC and the other obtained by ID. N gives the number of cylinders employed in its design, γ is the total radiation enhancement factor, HPAW define the half power angular width, and η_{+y} is the relevant radiation efficiency in the principal direction of emission (the positive y axis).

	Frequency (GHz)	N	γ	HPAW (deg)	η_{+y} (%)
PhC source	24.33	200	0.82	10.0	29.5
ID source	23.66	102	6.3	3.4	40.9

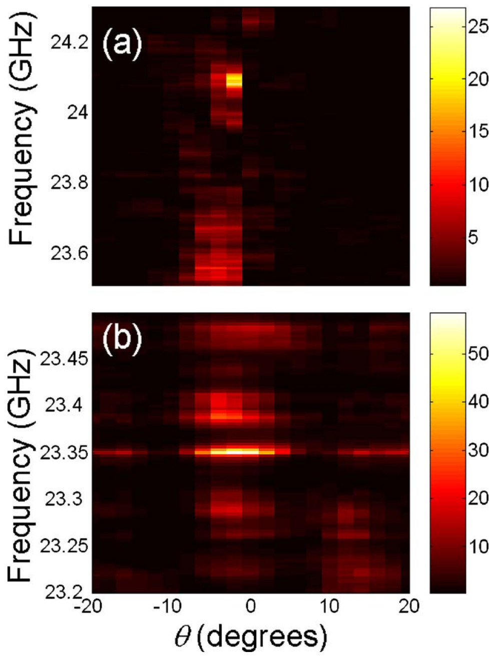

FIG. 4. (Color online) Maps of normalized measured power as a function of frequency and angle for a monopole inside the (a) PhC and (b) ID structure.

η_{+y}. Finally, the half power angular width (HPAW) for the forward peak is another parameter of interest. All these parameters are reported in Table I, which shows how the ID source outperforms the design based on a PhC. The frequency in each case corresponds to the intensity maximum.

Experimental measurements in the microwave regime were carried out to verify the beaming obtained from the numerical calculation. To this end, a 3 mm monopole was used as a point source and introduce inside the structure, which was placed upon a rotatory platform with a resolution of 2° so that the received power as a function of the angle could be measured. A highly directional horn antenna was placed at a distance of 1 m (about 80λ) from the monopole. Both antennas were connected to the ports of an HP8510C vector network analyzer. Figures 4(a) and 4(b) show the detected power normalized to the response of the isolated monopole as a function of the frequency and the rotation angle. For the case of the PhC, several high intensity spots were measured although only the two most intense are depicted in Fig. 4(a). This is because of the multiple reflections inside the PhC, which result in a Fabry–Pérot-like response.[9] The maximum intensity is 26 compared to the isolated monopole and is reached at $f=24.12$ GHz, which is close to the frequency of the intensity maximum obtained from numerical calculations, $f=24.33$ GHz (the deviation is below 1%). For the case of the aperiodic structure, a well defined single spot is observed, with a maximum intensity enhancement of 58.5 (17.65 dB) at $f=23.35$ GHz, in perfect agreement with the theoretical results. Figure 5 shows the measured intensity along the transverse direction at the frequency of the maximum for the ID structure. Measured power (logarithmic units) in the forward (blue curve), lateral

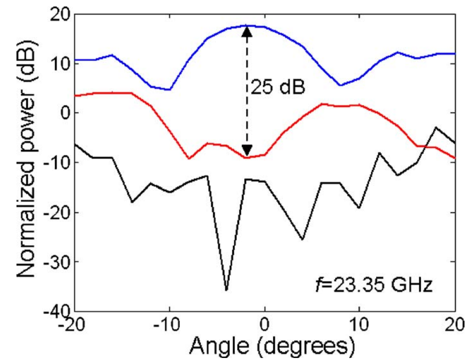

FIG. 5. (Color online) Transverse normalized intensity profiles for the ID structure (see Fig. 1) at the frequency where the maximum is obtained. The far-field detected power in the forward (blue line), lateral (black line), and backward (red line) directions is shown.

(black curve), and backward (red curve) directions is included. The half power beamwidth is about 7.5°. It is shown that lateral emission becomes negligible. In addition, backward emission is strongly suppressed, with a front-to-back ratio of about 25 dB. It has to be highlighted that when the source is created by use of the PhC, backward and forward emissions are approximately of the same order of magnitude, depending of the number of cylinder layers implemented at each side of the source inside the PhC. Thus, it is clearly demonstrated that ID permits a high improvement of the directional emission properties of EM sources embedded in periodic structures.

In conclusion, we have demonstrated that by using ID one can control the emission pattern of EM sources. Our experimental results in the microwave regime are encouraging taking into account that no control over the vertical direction was carried out. We conclude that the proposed approach is suitable to get control of the emitted radiation in optical elements such as lasers or light emitting diodes.

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