High order mode formation of externally coupled hybrid photonic-band-gap cavity

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The electromagnetic field distribution obtained from a finite-difference-time-domain simulation shows that a hybrid photonic-band-gap (PBG) cavity enveloped by a dielectric lattice and three metallic walls provides a better field uniformity of a high order mode, TM m0+n, than a conventional one does under an external coupling with the maintenance of a high quality factor of the metallic cavity. Experimentally measured reflection and transmission scattering matrices of a TM 550 mode show that the hybrid PBG structure improves the field uniformity to within 10% compared with a larger variation reaching a few tens of a percent with the conventional cavity under critical coupling. © 2007 American Institute of Physics. [DOI: 10.1063/1.2431451]

For the last decade, a photonic crystal (PC) 1,2, comprised of periodic metallic and/or dielectric lattices, has been paid a great deal of attention as an attractive light-controlling element in optics and nanoelectronics. Its peculiar optical properties, such as photon localization, spectral filterability, distorted dispersion, and modified photon mode, make various applications possible, for example, high efficient passive elements, high efficient radiation, second harmonic generation, applications possible, for example, high efficient passive elements, high efficient radiation, second harmonic generation, ultrafast switches, and so on. In particular, the photonic band elements, high efficient radiation, second harmonic generation, ultrafast switches, and so on. In particular, the photonic band gap (PBG) arising from multiple Bragg reflections of the PC has been considered for building microwave structures, 3–7 such as cavities, waveguides, and filters, thanks to its mode selectivity. Furthermore, recently the PBG structure has been considered for creating a high gradient resonator for use in accelerators. 8 In fact, a conventional (pillbox) cavity has long been utilized as a dynamic resonator for optical and microwave devices. Externally coupled, the cavity, however, has an abnormal mode formation perturbed by severe field distortion and so its response efficiency degrades steeply. Thus, there have been various attempts 9–12 to replace the metallic cavity with a PBG one. Despite theoretical and experimental progress, it is still difficult, even in the quasi optical structure, to couple a higher order cavity mode to a waveguide mode with a good field uniformity as well as to maintain a constant quality factor (Q factor) using a conventional metallic cavity.

In connection with this technical challenge, this letter presents, both numerically and experimentally, the optical signatures of a proposed hybrid PBG cavity surrounded by a dielectric PC lattice array and three metal surfaces. Numerical finite-difference-time-domain (FDTD) simulation of TM 550 mode (transverse magnetic mode) compares field uniformities of the pillbox cavity with the PBG one. In addition, we measure the transmission scattering matrices (S21) between a waveguide port, built on a line defect in the PC lattice, and the peaks of field distribution (TM 550 mode) in the PBG cavity and compare their amplitudes in the frequency spectrum.

The design process of the PBG cavity starts with a computational FDTD analysis of an optical response of a two-dimensional lattice array. At the TM 550 resonant frequency (e = 10.5 GHz) in our case, the dielectric square lattice with a rod radius of 1.9 mm is assumed to have a lattice constant d of 10 mm and the relative permittivity [Re(e) = 9.85, Im(e) < 0.001] and permeability (μr = 1) of alumina (Al2O3) at 10 GHz. Figure 1 shows global frequency band gaps for TM modes of the designed PBG structure, with the electric field parallel to the rods, and a transmission scattering matrix (S21) for the effective waveguide in the rod array, which is obtained from numerical simulations. 1,2,14 Figure 1 shows global frequency band gaps for TM modes of the designed PBG structure, with the electric field parallel to the rods, and a transmission scattering matrix (S21) for the effective waveguide in the rod array, which is obtained from numerical simulations. 1,2,14 Note that in the S21 frequency spectrum the line defect forms conspicuous transmission band, which corresponds to frequencies from 9.5 to 13.5 GHz, in the band gap of the first Brillouin zone, as if eigenmodes propagate through a conventional waveguide. On the other hand, the nonresonant scattering of photonic modes with a (210) reciprocal lattice vector in the waveguide considerably decreases the transmission coefficient at the band gap of the second Brillouin zone. We replace a metallic wall of a pillbox cavity with the dielectric PC lattice of six columns and combine a single line defect with the hybrid PBG cavity. A single rod remaining on the one-dimensional defect plays a central role.

FIG. 1. (a) Global frequency band gap of the designed PC lattice (e = 1.9 mm and d = 10 mm). (b) transmission frequency spectrum of TM mode through the PC lattices (1) with (dotted line) and (2) without a line defect (solid line).
in coupling between the cavity and the waveguide, and the coupling impedance can be adjusted by its size and material properties. For the comparison, we also model a metallic pillbox cavity coupled to WR-75 waveguide in the computational frame. With a resonant frequency of TM$_{550}$ mode, the area and thickness of the two cavities are respectively specified as $100 \times 100$ mm$^2$ and 10 mm. The thickness is arbitrarily determined, taking into account simulation feasibility because of no mode dependence in the longitudinal direction.

Figure 2 illustrates snapshots of the transverse electric field distribution in TM$_{550}$ mode, when excited by an external source through input ports of the waveguides, at the cavities. For the feasibility of the coupling structure, we consider symmetric odd modes. In Fig. 2(a), mismatching of boundary impedance owing to the waveguide hole severely distorts the field distribution near the cavity-waveguide boundary, worsening the entire field uniformity. On the other hand, in Fig. 2(b) the TM$_{550}$ mode pattern is distinctly formed with a uniform field distribution. A substantial improvement of field uniformity is shown in the latter from the computational comparison. Nevertheless, in Fig. 2(b) a substantial amount of distributed electromagnetic energy of the cavity seems to infiltrate into the PC lattice slab. Therefore, according to eigenmode numbers, $m$ and $n$, we compare the $Q$ factors (TM$_{mnm}$) of three cases: (1) pillbox, (2) conventional PBG, and (3) hybrid PBG cavities. Here, the cavities are supposed to be externally unloaded, so that the quality factor calculations only include Ohmic losses. In Fig. 3, it should be noticed that $Q$ of (3) is almost the same as that of (1), whereas (2) has a relatively lower $Q$, about 3% less than those of (1) and (3). This result implies that the hybrid PBG cavity provides a uniform field distribution even under the external coupling with the maintenance of a strong energy confinement.

For the experimental verification, we measure reflection and transmission scattering matrices, $S_{11}$ and $S_{21}$, of the TM$_{550}$ mode in the PBG cavity. Figure 4 exhibits the experimental setup and a conceptual drawing of its structure. In the test apparatus, for feasible fabrication, the metallic part of the cavity is made up of an Al-alloyed compound with a conductivity of $\sigma=3.72 \times 10^7$ $\Omega^{-1}$ m$^{-1}$, and alumina (Al$_2$O$_3$) is used for the dielectric rod of the PC lattice. Also, dimensional parameters and the geometrical structure of the lattice and the cavity are the same as in the computational model in Fig. 2. The effective waveguide of the line defect is coupled to a vector network analyzer (VNA) via the external port of the WR-75 waveguide. The 25 units of probe, equipped so that field strengths of TM$_{550}$ mode are maxima in the cavity, pick up an input signal generated from the VNA (port 1) and transmit them back to the VNA (port 2). The field perturbation due to the presence of the probes with 0.9 mm hole radius is within about 4.5%, which can be regarded as neg-
ligible. Figure 5 shows reflection ($S_{11}$) and transmission ($S_{21}$) frequency spectra measured at the five sampling points of the cavity center, which represent field configurations of the other 20 points. In the spectrum, because of cavity-waveguide coupling, two very distinct peaks appear: the lower peak at $f=10.55$ GHz and the higher peak at $f=10.59$ GHz, corresponding respectively to the waveguide mode and the cavity mode. Note that at the TM$_{550}$ resonant frequency ($f_{550}$) of 10.59 GHz, the transmission signal amplitudes ($S_{21}$) of the five points are almost the same within a 10% field uniformity under critical coupling ($\gamma=S_{11}=0.17$) between the cavity and the waveguide. The uniformity, though slightly larger than our analysis, is fairly consistent with computational predictions. The experimental measurement explicitly demonstrates that a hybrid PBG structure constitutes a nondispersive quasioptical bound state, which can form an exact cavity eigenmode regardless of an external coupling.

As a summary remark, we numerically and experimentally corroborate that our conceptual approach combining the conventional metallic cavity with the PC structure provides outstanding field uniformity of a higher order cavity mode, even if externally coupled, maintaining the high $Q$ of a metallic cavity. It is promising that the idea might be applicable to optical and microwave devices for efficient passive and active elements.

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