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Highly confined mode above the light line in a two-dimensional photonic crystal slab

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We found that certain modes above the light line can satisfy total internal reflection in a two-dimensional photonic crystal slab, resulting in negligible vertical leakage. A heterogeneous cavity utilizing such a mode was designed and constructed for the microwave spectrum. Numerical calculations show the mode has a quality factor (Q) of 6×10^5 neglecting the material loss and 7600 including it. The measured Q (9000), resonance frequency, and mode pattern agreed well with the calculation. The mode has more than 50% of electric field energy in void space and is promising to have stronger interaction with materials introduced there. © *2008 American Institute of Physics*. [DOI: 10.1063/1.3046124]

A two-dimensional (2D) photonic crystal (PhC) slab has emerged as one of the most promising platforms to fabricate an optical microcavity. The light can be confined inside a small volume for a long time and build up an intense optical field. Since a 2D PhC slab consists of a periodic array of air cylinders or dielectric pillars, there is vast percentage of void space inside the cavities, where other materials can be easily introduced. The interaction between the optical field and the introduced materials can be enhanced greatly dependent on their spatial overlapping, the quality factor (Q) of the cavities, and mode volume. There have been proposals to use the high Q and field enhancement for applications such as sensing of introduced biochemical materials,[1,2] enhancing the light emitting efficiency of the introduced quantum dots,[3,4] and tuning the cavity by thermally or electrically tuning the infiltrated liquid crystals.[5]

To confine the modes vertically, most research groups used modes below the light line to satisfy total internal reflection (TIR) condition at the top and bottom slab interfaces.[6–8] In the design, the majority of the electric field energy concentrates in dielectric materials to lower the mode's frequency compared with the light line and decrease the vertical scattering. In those cases, the overlapping between the field and the materials introduced is limited. To have more electric field energy inside void space, the modes above the light line provide better choice, which have not been fully exploited since they were widely believed to inherently leak vertically for not satisfying TIR condition.[9]

In this letter, we showed that some specific modes above the light line can still be totally internal reflected at the slab interfaces. With the theoretical finding, we designed a cavity to confine such a mode both horizontally and vertically and tested it in the microwave spectrum. To the best of our knowledge, it is the first cavity design targeting the modes above the light line. The experimental results agree well with the theoretical findings.

The PhC that we consider is a square lattice of dielectric rods, as shown in Fig. 1(a). The 2D bandstructure corresponding to infinitely long rods is computed using the MIT photonic band software.[10] We can use the 2D bandstructure to estimate the in-plane dispersion of the corresponding modes in the slab. As shown in Fig. 1(a), we investigate the second band edge mode at $\vec{K}=0$ (Γ point), called the γ_2

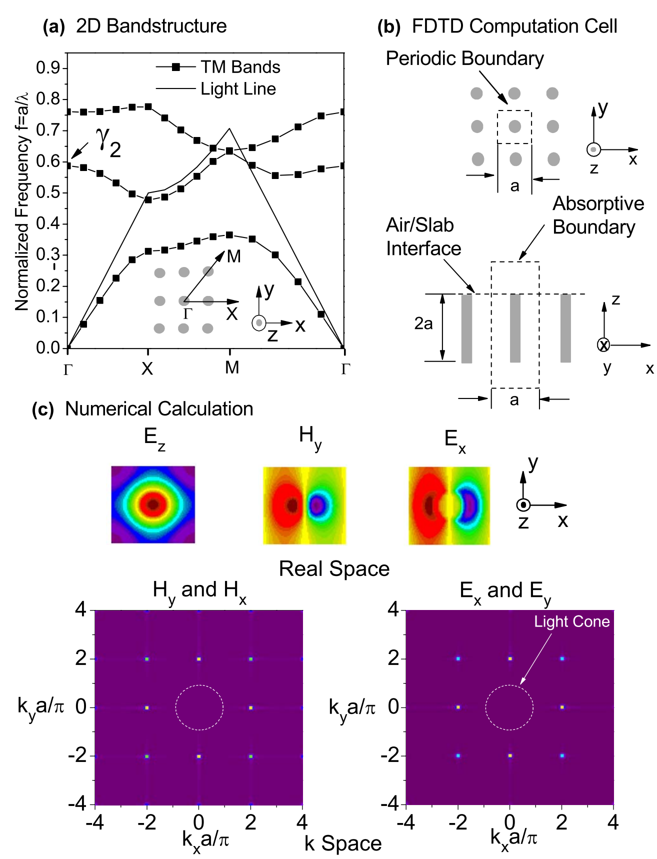

FIG. 1. (Color online) (a) The 2D bandstructure of a PhC consisting of a square lattice of alumina rods with refractive index $n=3.211$ and radius of $0.15a$, where a is the period. (b) The horizontal (top) and vertical (bottom) cross section of a 3D FDTD computation cell, which is the unit cell of the periodic PhC slab, containing one rod. (c) Spatial distribution of the field components at the slab/air interface (top). $\vec{k}$ distribution of the transverse field components (bottom).

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mode, where the letter denotes the crystal wave vector and the superscript indicates the band number.

By conventional wisdom, since $\vec{K}$ is zero and the mode is above the light line, a large loss in the vertical direction would be expected. However, theoretically, it has been found that certain modes above the light line can have extremely long lifetimes for their spatial symmetry, which is mismatched with the plane waves in air.[11–14] To judge whether a mode satisfies TIR condition, we believe that it is inappropriate to compare crystal wave vector $\vec{K}$ of a Bloch mode in a PhC slab directly with wave vector $\vec{k}$ of a plane wave mode in air. Instead, a more proper approach is to first decompose the Bloch mode into plane wave components by Fourier analysis and then compare those with the corresponding plane waves in air. A similar method has been used to find the leaky components of the confined modes below the light line.[8,15,16]

The spatial distribution of a field is needed to obtain its distribution in k space. We now use the three-dimensional (3D) finite difference time domain (FDTD) method to obtain the transverse field components at the slab/air interface. The computational cell is displayed in Fig. 1(b). In the x-y direction, periodic boundary conditions with phase shift between neighboring cells equal to 0 are used, computing the desired Γ modes. In the vertical direction, perfectly matched layers are used to absorb any outgoing energy. More details about the calculation can be found in Ref. 17. As shown in Fig. 1(c), the transverse magnetic and electric field components of γ_2 mode are antisymmetric, among which H_y and E_x are shown in the figure. The transverse fields of the γ_2 mode was decomposed by Fourier transformation and their plane wave $\vec{k}$ components are displayed. The results in Fig. 1(c) show, because of antisymmetry, the $\vec{k}=0$ component is totally inhibited. All of the $\vec{k}$ components are outside the light cone, satisfying the TIR condition and implying negligible vertical leakage.

The quality factor (Q) of the γ_2 mode can also be calculated with 3D FDTD with the same computational cell.[17] It can be used to quantify the leakage of the confined energy. Because of periodic boundary conditions, there is no power loss in the horizontal directions. The computed Q thus only evaluates the power loss in the vertical direction. From the simulation, we found that the γ_2 mode has a Q exceeding 10^9, verifying it is a genuine guided mode with negligible vertical leakage, anticipated by the above $\vec{k}$ space analysis.

In the following, we designed a finite sized cavity to confine such a mode. The heterogeneous cavity constructed by alumina rods (Anderman Ceramics) is shown in Fig. 2(a). A large stop gap exists above the γ_2 mode in the ΓX direction. As seen in Fig. 2(b), the γ_2 mode in the core region is in the stop gap of the cladding wall region because of the different periods.[18] As a result, the wall acts as an effective reflector and the γ_2 mode is strongly confined in the core region. The fundamental mode pattern is calculated by 3D FDTD and shown in Fig. 2(c), which is a γ_2 mode modulated by an envelope function.[17] By Fourier transformation, we can obtain the $\vec{k}$ distribution of the confined mode. Because of its finite size, the translational symmetry is broken and it introduces small but finite components around the $\vec{k}=0$ point as shown in Fig. 2(c). These components are inside the light cone and will cause vertical leakage of the confined mode.[8]

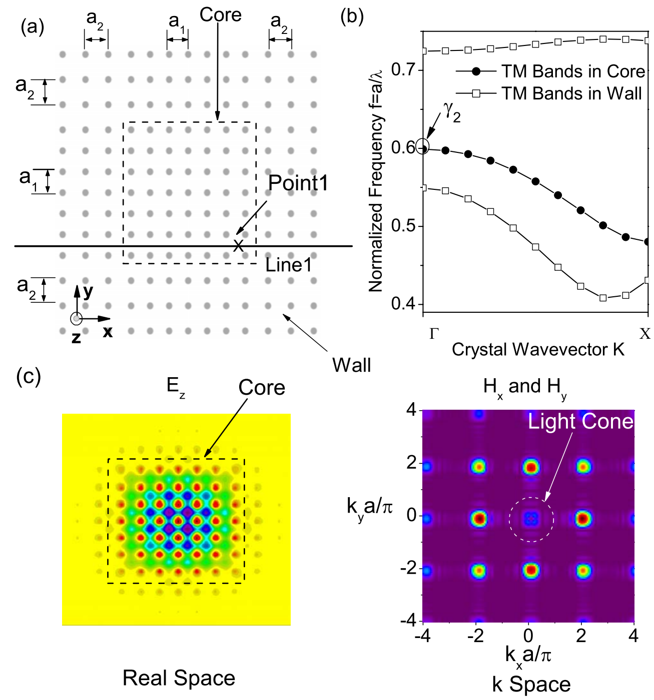

FIG. 2. (Color online) (a) The top view of the heterogeneous cavity used in the microwave measurement. The alumina rods have a diameter of 2.4 mm and length of 48 mm. The core region has a period $a_1=8$ mm and the outside "walls" have a larger period $a_2=1.2a_1$ perpendicular to the interface and the same period a_1 parallel to the interface. The real part of the refractive index of the alumina rods is 3.112. (b) The 2D bandstructure of the core region and the wall region along Γ-M direction. (c) The spatial distribution of E_z of the fundamental cavity mode (left) and the $\vec{k}$ distribution of the transverse magnetic field H_x and H_y of the mode.

We calculate the quality factor (Q) of the fundamental mode by 3D FDTD. The total Q can be separated into two parts as $1/Q=1/Q_{\parallel}+1/Q_{\perp}$, where $Q_{\parallel}$ accounts for the horizontal power leakage and $Q_{\perp}$ accounts for the vertical leakage. Neglecting material absorption, we find that the total Q is about 600 000 with $Q_{\perp}\sim 1.2\times 10^6$ and $Q_{\parallel}\sim 10^6$. The γ_2 mode is strongly confined horizontally and vertically. The decreased $Q_{\perp}$ of the confined mode compared to the extended one is due to the finite plane wave components inside the light cone. The inclusion of alumina material absorption in the 3D FDTD simulations, described by an imaginary refractive index part ($k=0.000\,438$), substantially decreases the Q value to about 7600 at $f=21.8$ GHz. The above dielectric constant data were provided by the supplier, which are consistent with the data reported in the literature.[19] About 52% of the electric energy locates in void space, which occupies about 92% of the total space.

This cavity was fabricated for use in a microwave experiment. The alumina rods were supported by two parallel low loss dielectric sheets (Rogers RT/duroid 5880 high frequency laminates) with holes drilled, as displayed in Fig. 3(a). A line was drilled into the top sheet to allow access through the surface and inside the slab. Measurements were done by inserting a coaxial monopole antenna probe into the PhC slab with a K-band horn antenna as an exciting source. A vector network analyzer (Agilent PNA E8364B) was used to measure the reflection coefficient (S_{11}) with only the monopole antenna or the transmission coefficient (S_{21}) from the horn antenna to the monopole antenna. Time-domain gating was also applied to remove the early time response, leav-

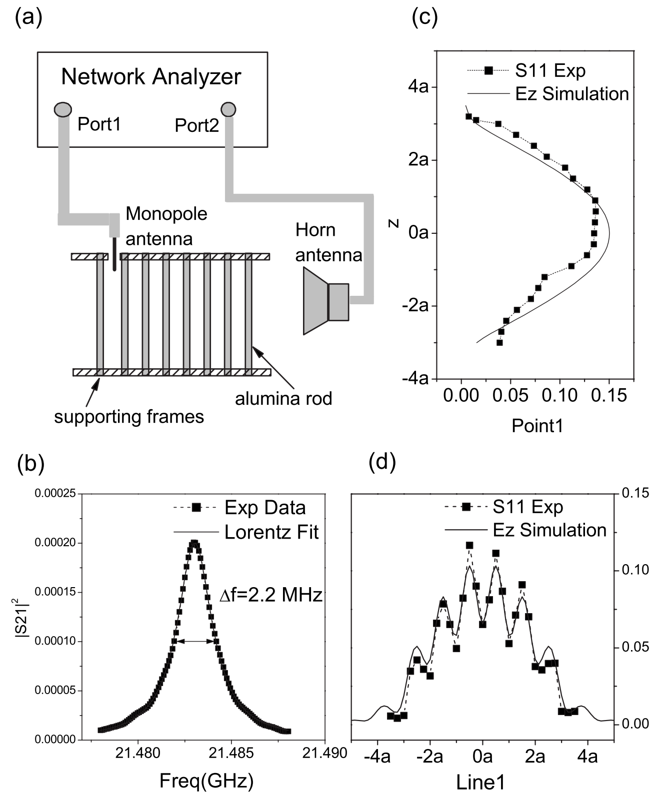

FIG. 3. (a) The schematic view of the microwave experiment setup. (b) The spectrum result. (c) The field distribution measured along a vertical line at point 1 shown in Fig. 2(a). (d) The field distribution measured at the top surface of the slab along line 1 shown in Fig. 2(a). In the axes of (c) and (d), a is a length unit indicating the period of the PhC.

ing only the long lifetime signal, which corresponds to the high-Q mode. As shown in Fig. 3(b), the fundamental mode resonance peak is at $f=21.48$ GHz and has a full width at half maximum of $\Delta f=2.2$ MHz, giving a $Q=f/\delta f$ of about 9000, a little larger than the simulated one. To measure the field distribution, we moved the monopole antenna at different positions along a vertical line and a horizontal line within the cavity, as shown in Fig. 2(a). The resonance peaks at these positions were recorded and the magnitude of the peak was taken to be proportional to the magnitude of local electric field E_z. As plotted in Figs. 3(c) and 3(d), the measurements are in good agreement with the simulation. The mode is a modulated γ_2 mode, tightly confined in the core region horizontally and in the slab vertically. It is worth noting that if all the electric field energy concentrated in the alumina rods, the Q should not exceed $Q_{\mathrm{absorption}}=n_{\mathrm{real}}/2n_{\mathrm{imag}}$,[20] which is about 3600. The calculated value of 7800 and the measured value of above 9000 confirms that more than half of the electric field energy concentrates in air and therefore the mode is less influenced by alumina absorption.

In summary, to find whether a mode satisfies TIR in a 2D PhC slab, it is needed to decompose the mode into plane wave components and then compare with the plane waves in air. With such a method, it was found that certain modes above light line could satisfy TIR condition with all plane wave components outside the light cone. A heterogeneous cavity was constructed in the microwave spectrum to confine such a mode. The theoretical and experimental results showed that the mode was highly confined both horizontally and vertically. Neglecting the material absorption, the cavity can reach a Q of more than half a million. With a transparent high quality semiconductor such as crystalline silicon at 1.5 μm, it is feasible to fabricate a high Q microcavity to confine such a mode in optical domain. In addition, the mode has more than half of its electrical field energy in void space and is ideal for applications, which need large overlapping between the electric field of the mode and the materials introduced. The Fourier analysis employed here can be used further to optimize the design for a larger Q, a smaller mode volume with rods of smaller aspect ratio. Our finding expands the possible frequency range to construct a PhC microcavity with modes having new properties.

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