High-Q Photonic Bandgap Resonant Cavities: from mm-wave to Optical Regime

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Abstract

We have realized a new class of high-Q resonant cavity using two-dimensional photonic bandgap (PBG) structures and showed that its Q-value can be as high as ~23,000 in the mm-wave regime. We further show that its modal properties, such as the resonant frequency, modal linewidth and number of modes, can be tuned by varying the cavity size. In addition, we present a new nano-fabrication technique for constructing PBG resonant cavities in the near infrared and visible spectral regime.

Introduction

The photonic bandgap (PBG) structure is a new class of photonic materials that exhibits energy-band like dispersion relationship for the propagation of electromagnetic waves (EM) [1]. In the photonic band gaps regime, the EM-waves decays exponentially and no propagation is possible. Consequently, a photonic bandgap may be viewed as a perfect mirror [2] which reflect all the incident lights back with little loss. In this regard, PBG materials are particularly useful for constructing high-Q resonant cavities for applications such as single-mode thresholdless semiconductor lasers, light-emitting-diodes [3], and high-Q band pass filters [4].

In this paper, we first report our results of mm-wave transmission measurements of 2D PBG-cavities with cavity-Q as high as 2.3×10^4 in the mm-wave regime. We show that by varying the cavity size, a single mode operation is possible. In the optical regime, we present our preliminary results on the nano-fabrication of photonic lattices at a length scale of ~100 nano-meter using a new technique, namely, electron-beam induced deposition.

Samples and Experiment

For our mm-wave experiment, we have constructed two different types of resonant cavities, shown in Fig.1(a) and 1(b), from a 2D photonic lattice. The former is analogous

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to a 1D Fabry-Perot resonator and the latter to a 2D planar resonator. Its corresponding band alignment is shown in Fig.1(c). Quasi-bound states are formed in the photonic band gap regime due to size quantization [5]. As a result, highly peaked photonic density of states can exist in the otherwise forbidden bandgap regime. The 2D photonic lattice consists of 10 cm long cylindrical alumina-ceramic rods (ε=10) arranged parallel to one other in a square lattice structure with lattice constant a_o = 1.27mm and rod diameter d=0.51mm. The values of a_o and d are chosen to yield a large photonic band gap around 75-110 GHz which falls in the frequency range of our mm-wave test set.

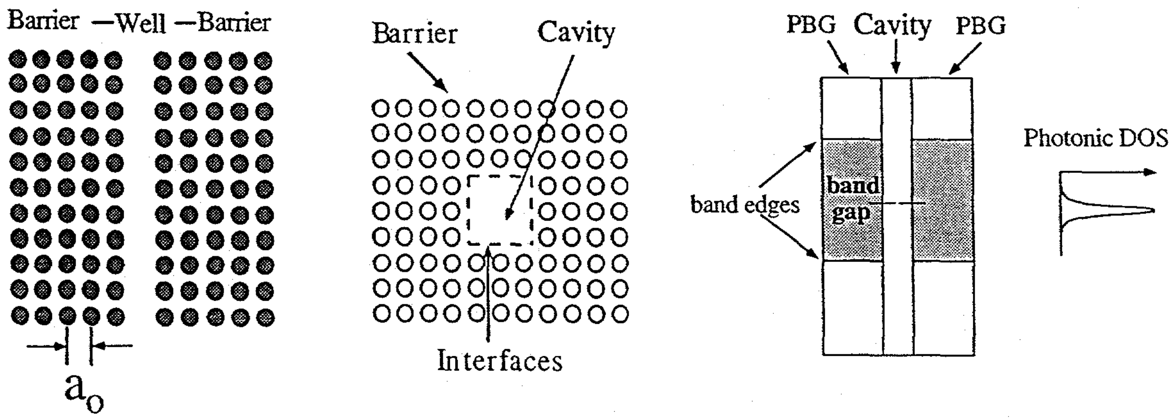


Fig.1 (a) A photonic quantum well structure, having its quantum well sandwiched in between two PBG-barriers with a large photonic gap. (b) a photonic quantum dot structure. (c) a corresponding band alignment, showing a bound state is formed in the otherwise forbidden bandgap regime.

An HP 8510C millimeter-wave network analyzer system is set up for the mm-wave transmission measurement. The sample is placed in the beam path between two horn antennae, (a transmitter and a receiver), and is surrounded by absorbing pads for shielding purposes. The radiation from the antenna is broadband, (75-110GHz), well polarized (polarization rejection ratio in excess of 50dB) and has a good spectral resolution (18Hz) and purity. Additionally, the analyzer has a wide dynamic range of > 60dB and is capable of detecting weak transmitted signals.

PBG-Cavities in the mm-wave Regime

In Fig.2, we show the transmission amplitude of EM-waves through a photonic quantum well structure with barrier thickness W_b=4a_o and quantum well thickness L=2a_o. The electric field of the radiation is polarized parallel to the axis of rods, i.e. TM mode. This data shows that the 2D photonic lattice has a large TM fundamental photonic bandgap (> 35GHz) with its upper band edge located at ~ 105GHz. The transmission peaked at f=85.5GHz is sharp, follows a Lorentzian lineshape (see inset) and has a cavity Q-value of 3,700. We have repeated the same measurement for samples with different W_b, from 3a_o to 8a_o. A plot of the deduced cavity-Q vs W_b shows that while cavity loss is dominated by leakage of light through tunnel barriers at small W_b, dielectric loss becomes important at larger W_b and eventually sets the limit for the highest obtainable Q-value [6]. The highest-Q that we measured is 23,000.

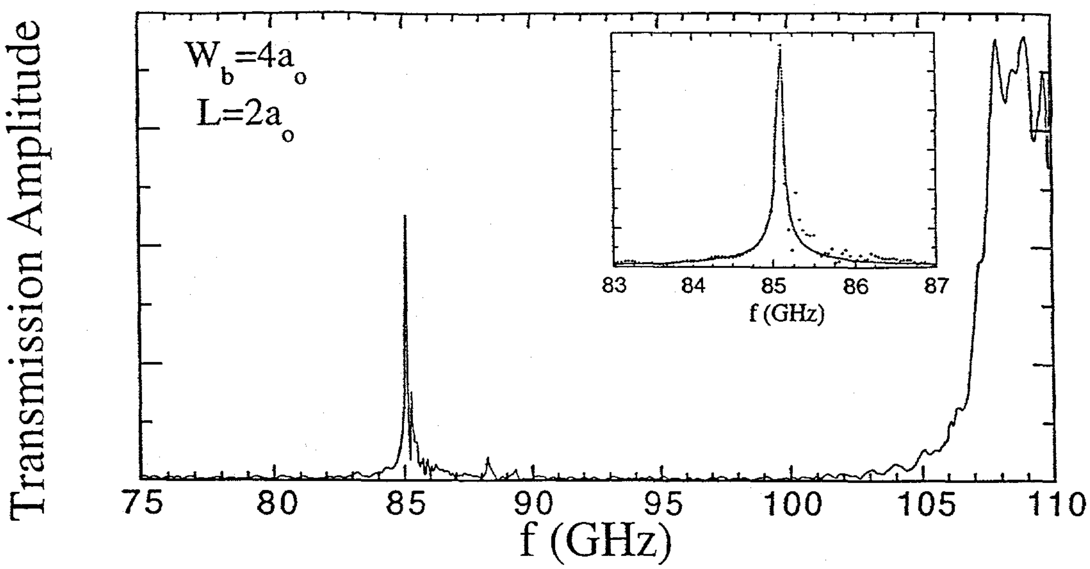


Fig.2 Transmission amplitude vs frequency taken from a photonic quantum well sample. The sharp transmission peak at 85GHz corresponds to resonant transmission of EM-waves through a quasi-bound states formed in the bandgap regime of the PBG-barriers.

In Fig.3, we show similar transmission results taken from samples having different quantum well thickness, L= 2, 4, and 6 a_o. In all cases, we observed sharp, discrete transmission peaks in the photonic bandgap regime, a characteristic feature of a quantized system. We also note that as L is increased, the corresponding modal structure changes from a single, double, and to triple modes for the widest QW sample, $L=6a_o$.

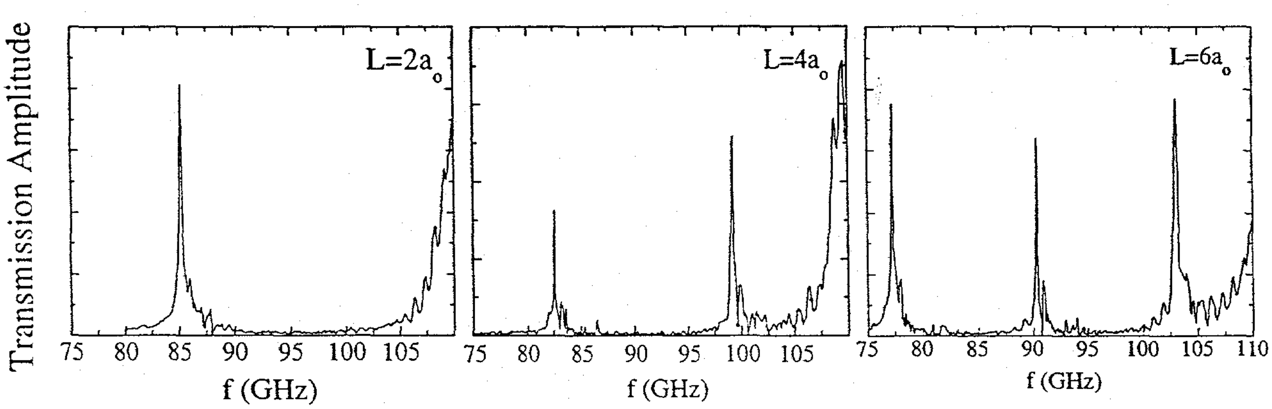


Fig.3 Transmission amplitude vs frequency taken from samples with different quantum well thickness, $L=2a_o$, $4a_o$, and $6a_o$.

We now come to the 2D confined structure shown in Fig.1(b) and study its modal structure. One series of sample has a 2D cavity size ranging from $(1 \times 2)\ a_o^2$ to $(1 \times 8)\ a_o^2$ and the other from $(2 \times 2)\ a_o^2$ to $(2 \times 8)\ a_o^2$. In Fig.4, the measured resonant frequency is plotted as a function of cavity size for both sample series. As expected we observe a steady increase in resonant frequency as the cavity size is reduced, making it possible to tune the resonant frequency throughout the photonic band gap regime. We note that within this tuning range, a single resonant mode is maintained.

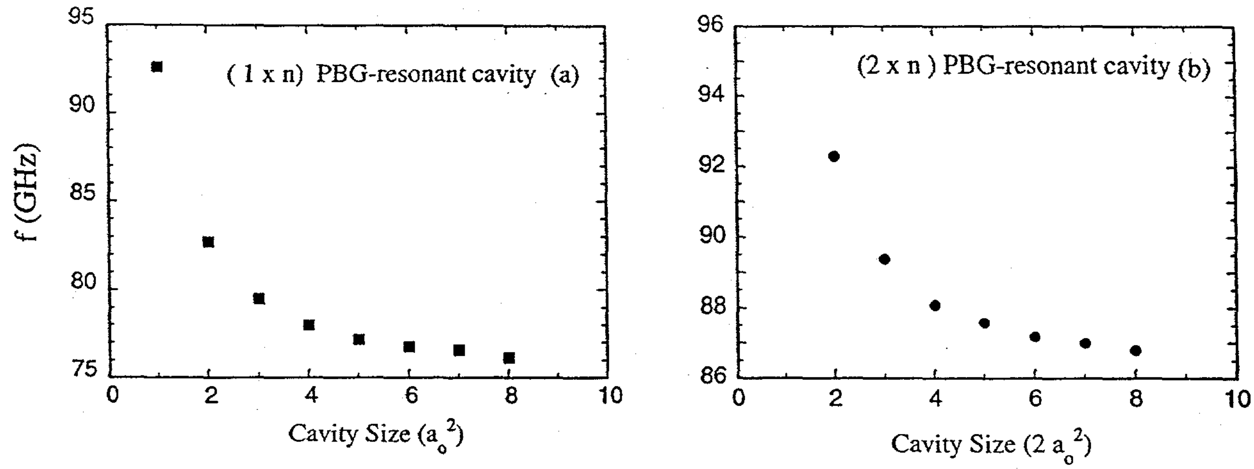


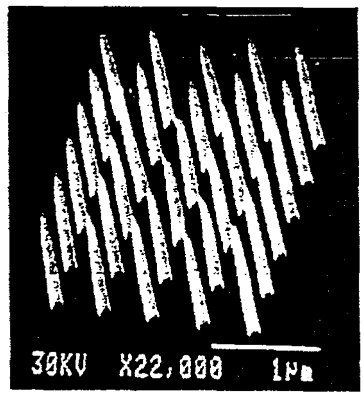
Fig.4 Resonant frequency vs cavity size for two series of 2D resonant cavity: (a) a (1 x n) PBG quantum dot structure and (b) a (2 x n) PBG quantum dot structure.

PBG Structures in the Optical Regime

To make PBG devices more useful, one need to realize it in the optical regime. Since its characteristic feature size is small, typically about 100nm, such structures continue to challenge our state-of-art nano-fabrication capability. One commonly adopted fabrication scheme is to combine electron-beam lithography with reactive-ion-beam etching along one or more directions into a substrate material. Although certain progress has been made [7],the major challenge of achieving a straighter sidewall and a larger aspect ratio still remain. Here, we propose a different approach. Instead of undergoing nano-fabrication, we perform nano-growth using an electron-beam induced deposition technique.

This technique directly grow the nano-lithographic structures of photonic crystal under computer control. The growth system is built from a JOL JSM-840F scanning electron microscope. The detail of this technique has been described elsewhere [8.9]. But in short, high energy electron beams (500-35KV) are utilized to decompose a precursor material and subsequently induce material deposition. It allows nm-precise placement of photonic crystal into prefabricated structures, such as waveguide pattern. It also allow massive parallel electron beam deposition, as they are available in a reducing image projection system with a stencil mask[10]. This way, photonic crystal with artificially designed bandgap can be investigated and produced economically.

We now show two SEM images of our preliminary growth results. Fig.6(a) shows a picture of a 2D photonic crystal built on the edge of a Si wafer. It consists of a 5 x 6 array grown from cyclopentadienyl-platinum-triethyl at 30KV and 140pA, with a lattice constant a_o = 490nm and rod diameter d=120nm. The structure is designed to have a mid-gap centered around λ=1400nm, assuming the index of refraction of the deposited material is ε=4-8. The length scale is also shown in the figure. Fig.6(b) is the top view of the photonic crystal, showing the perfect periodicity of the structure. We believe that this technique hold great promise for the realization of PBG devices in the optical regime. One example of its application would be to integrate light emitters, such as LEDs or semiconductor lasers, in an PBG-environment for better light confinement and higher emitting efficiency.



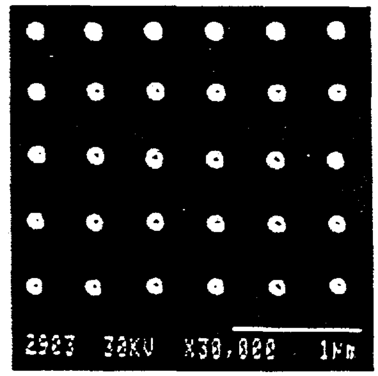


Fig.5 SEM images of a 5x6 photonic crystal fabricated on the edge of a Si wafer using an electron-beam induced deposition technique. The material been deposited is cyclopentadienyl-platinum-triethyl.

Summary

In summary, we have tested a series of PBG resonant cavity and show that such cavity can be of single mode and high-Q in the mm-wave regime. Furthermore, we present our preliminary results on the nano-growth of photonic crystals using an electron-beam induced deposition technique. The photonic crystal is expected to have its fundamental gap at λ~1.4 μm.

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