Photonic band gap quantum well and quantum box structures: A high-Q resonant cavity

Shawn-Yu Lin, V. M. Hietala, and S. K. Lyo
Sandia National Laboratories, P.O. Box 5800, Albuquerque, New Mexico 87185

A. Zaslavsky
Brown University, Division of Engineering, Providence, Rhode Island 02912

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We have tested a series of high-Q photonic band gap (PBG) resonant cavities in the mm-wave regime and achieved a cavity-Q of 2.3×10^4, the highest value reported among all two- and three-dimensional PBG cavities. We have also systematically varied the size and reflectivity of such cavities to study their effect on cavity properties such as cavity modal frequency, linewidth, and cavity Q value. We show that the resonant frequencies can be tuned throughout the PBG regime and that linewidths (or equivalently Q value) can be varied over two orders of magnitude (i.e., a Q value from $\sim2.7\times10^2$ to 2.3×10^4). © *1996 American Institute of Physics.* [S0003-6951(96)04223-4]

There is a great deal of current interest in photonic band gap (PBG) materials for fundamental physics study[1] as well as for photonic device applications such as high quality (Q) resonant cavities, light-emitting diodes,[2] and integrated minature spectrometers.[3] A PBG material is an artificially engineered periodic dielectric array that poses frequency gaps in which the propagation of an electromagnetic (EM) wave is evanescent. Such a photonic band gap may be viewed as a perfect mirror[4] and is particularly useful for constructing the high-Q resonant cavities[5] in the optical regime since in this wavelength range metals are very lossy and dielectric layers tend to give poor optical confinement in the sub-micron range. Even in the mm-wave and microwave regime, a high-Q resonant cavity is usually made from superconducting materials which can be quite difficult to fabricate and costly to operate since cryogenic operation is required. By contrast, a PBG cavity is low loss, compact, operates at room temperature, and can be of very high Q.[6,7] Experimentally, Yablonovitch *et al.* have realized the first PBG cavity in the microwave regime by introducing point defects into an otherwise periodic three-dimensional (3D) photonic lattice.[5] Subsequently, Smith *et al.* extended their study of high-Q defect modes to 2D photonic lattices.[8] In both cases, cavity Q was found to be ~1000 in the 10–18 GHz frequency range.

In this letter, we report our results of mm-wave transmission measurements of 2D PBG cavities with cavity Q as high as 2.3×10^4, to our knowledge the highest value reported among all 2D and 3D PBG resonant cavities to date. This Q value is found to be limited by the loss tangent of the dielectric material, alumina ceramic, used in constructing our 2D photonic lattice but not by the PBG structure itself. Additionally, our preliminary data show that the cavity resonant frequencies can be tuned throughout the PBG regime and its linewidth (or equivalently Q value) be varied over two orders of magnitude.

The 2D photonic lattice consists of 10-cm-long cylindrical alumina-ceramic rods arranged parallel to one another in a square lattice structure with lattice constant $a_0=1.27$ mm and rod diameter $d=0.51$ mm. The values of a_0 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. From such a 2D photonic lattice, we construct two different types of resonant cavities, one is the photonic quantum well (QW) structure shown in Fig. 1(a) and another the photonic quantum box (QB) structure shown in Fig. 1(b). Here, we adapt the following notation: a m-(i)-n photonic QW structure has i rows of empty lattice sandwiched in between m- and n-rows of barrier material; a *($m\times n$)* photonic-QB structure means that the resonant cavity has a physical size of *($m\times n$)* a_0^2.

The concept of the photonic QW structure has been described in detail in a previous publication.[9] Here, we only outline its basic principles: a photonic band gap can be regarded as a potential barrier for the propagation of EM waves and be utilized to quantize the continuous states of a suitably chosen quantum well material into a series of photonic bound states, much like the way potential barriers are

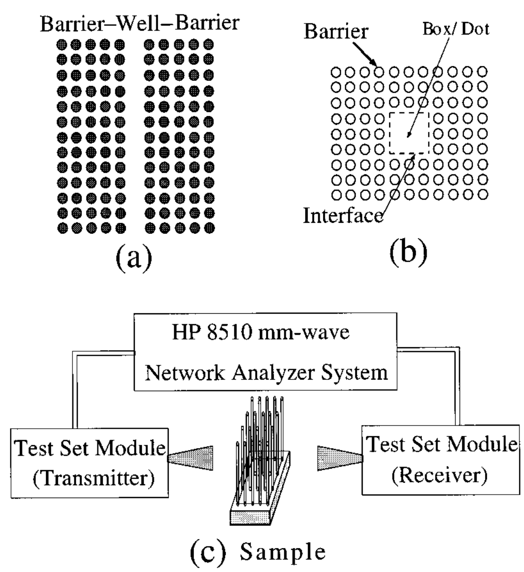

FIG. 1. A schematic of ''photonic heterostructures,'' that are created by imbedding one kind of PBG material, (a) quantum well or (b) quantum box, inside another PBG material of a large photonic band gap. In this experiment, both the quantum well/box material is chosen to be empty lattice. (c) A schematic of our millimeter-wave transmission measurement setup.

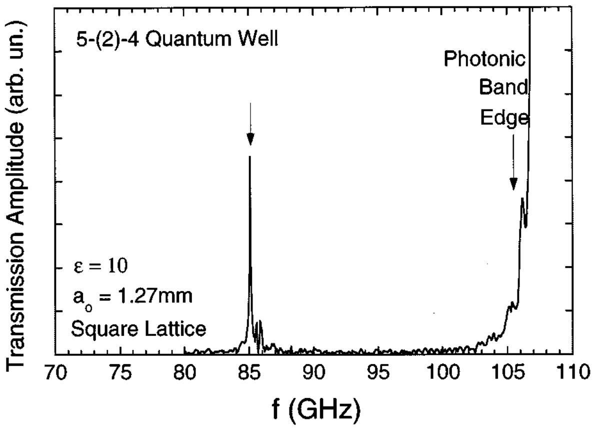

FIG. 2. Amplitude transmission of millimeter-wave through a 5-(2)-4 resonant cavity built from a two-dimensional periodic dielectric array. The single sharp peak, at f=85.5 GHz, lies in the photonic band gap spectral regime and corresponds to the resonant transmission of EM waves through a quasi-bound state in the cavity.

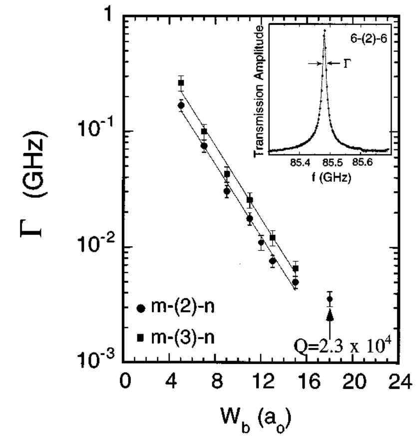

FIG. 3. Linewidth (Γ) as a function of total barrier thickness plotted in a semilogarithmic scale for both m-(2)-n and m-(3)-n photonic QW samples, circular dots, and square dots, respectively. The dashed line is a least-square fit to an exponential function. The sharpest linewidth of Γ=3.5 MHz corresponds to a cavity Q value of 2.3×10^4.

used to quantize the electronic states of a semiconductor quantum well. The QW material may be thought of as line defects, as opposed to point defects, introduced into an otherwise periodic photonic lattice structure.

There are several advantages of using such a new structure. First, its barrier thickness can be systematically increased or decreased to study its effect on cavity modal linewidth. By changing the QW width, the quantized levels can also be tuned throughout the photonic band gap spectral regime. A further confinement of EM waves can be achieved by constructing photonic QB structures with modal volumes approaching a few λ^2; here λ is the EM-wave wavelength. The size of the modal volume provides us with an additional degree of freedom in tailoring the frequency, linewidth, and number of modes of a resonant cavity.

A schematic of our experimental setup for the mm-wave transmission measurement is shown in Fig. 1(c). The sample is placed in the beam path between two horn antennas, (a transmitter and a receiver), and is surrounded by absorbing pads for shielding purposes. The antenna's opening has a physical dimension of 1×3/4 in. and they are separated by 12 in. An HP 8510C mm-wave network analyzer system is set up to measure the transmitted signal between these two antennas. The radiation from the antenna is broadband, (75–110 GHz), well polarized (polarization rejection ratio in excess of 50 dB), and has a good spectral resolution (18 Hz) and purity. More importantly, this analyzer has a wide dynamic range of >60 dB and is capable of detecting weak transmitted signals. These features are of essential importance to our measurement since transmission through a high-Q resonant cavity is often weak and its linewidth very narrow.[10]

In Fig. 2, the transmission amplitude of EM waves through a 5-(2)-4 photonic quantum well structure is plotted as a function of frequency (f) from 70 to 110 GHz. The electric field of the radiation is polarized parallel to the axis of rods, i.e., TM mode. This two-dimensional photonic lattice exhibits a large TM fundamental photonic band gap (>35 GHz) with its upper band edge located at ~105 GHz. The lower photonic band edge is expected to be at 65 GHz but is not observed here since it is out of our spectroscopic range. The sharp transmission peaked at f=85.5 GHz corresponds to the resonant transmission of the EM wave through a quasi-photonic bound state in the quantum well. The peak transmission amplitude is about 7% of the incident mm-wave beam intensity. The two small side peaks at the higher frequency side may be due to a small variation, $dW/W\sim0.1\%$, of the cavity size across our mm-wave beam spot of (3 cm)^2. We note that in our previous picosecond measurement of a similar sample structure,[9] the frequency resolution was limited to 5 GHz and therefore this yielded no information on the intrinsic linewidth of the cavity mode.

The transmission peak follows a Lorentzian line shape, a characteristic feature of damped resonant systems, and its fit is shown in the inset of Fig. 3 as a solid line for a 6-(2)-6 QW sample. The deduced linewidth (Γ), i.e., full width at half maximum power (or full width at 0.707 maximum E field) is plotted as a function of barrier thickness W_b as circular dots. We observe a dramatic narrowing of Γ over two orders of magnitude as W_b is increased from $5a_0$ to $\sim14a_0$. As W_b is further increased, the linewidth narrowing starts to slow down and saturate at a value of about 3.5 MHz. The smallest linewidth corresponds to a cavity Q value of 2.3×10^4 which is consistent with the loss tangent, $\sim1.0\times10^{-4}$ at f=8.5 GHz, of the dielectric rods.[11] If dielectric loss can be further improved, a Q value of 10^6 can be achieved for a W_b of about $20a_0$.

The observed exponential dependence of Γ on W_b at smaller W_b is a general characteristic of tunneling behavior. The straight line in Fig. 3 is a least-square fit of our data (from $5a_0$ to $15a_0$) to an exponential function: $\Gamma=\Gamma_0\times e^{-bW_b}$ using two fitting parameters $b=(3.0\pm0.2)$ cm^{-1} and $\Gamma_0=(2.7\pm0.2)$ GHz. We also show in Fig. 3 measurements on similar QW sample structures, i.e., the m-(3)-n QW samples, giving qualitatively similar results. Again, we see that Γ follows an exponential dependence on W_b and the deduced b of 3.0 ± 0.2 cm^{-1} is similar to that obtained from m-(2)-n sample. The only major difference is that the Γ for the m-(2)-n sample is always narrower than that for the

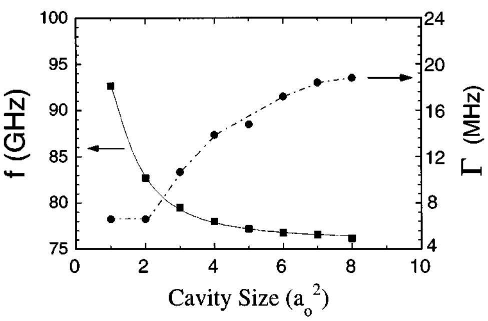

FIG. 4. Linewidth (Γ) and resonant frequency (f) plotted as a function of cavity size for a series of photonic quantum box samples. The solid line is a model fit to a two-dimensional resonator and the dash line is only a guide to the eyes.

m-(3)-n sample. This is also evident from the measured Γ_0 which is (2.7±0.2) GHz for the m-(2)-n QW sample and (4.0±0.2) GHz for the m-(3)-n QW sample. These data show that, while cavity loss is dominated by leakage of light through tunnel barriers at small W_b, other loss mechanisms, such as the dielectric loss, become important at larger W_b and eventually set the limit for the highest obtainable Q value.

We now address loss associated with light leakage along the plane of the QW. Since our incident mm-wave beam is not aligned perfectly parallel to the surface normal of the QW structure, some portion of the off angle EM wave would leak out of the well through waveguiding and thus contributes to loss. One way to resolve this problem and thus enhance cavity Q is to block the leakage from both sides of the well by constructing a photonic quantum box structure. In Fig. 4, we show the measured resonant frequency and cavity linewidth as a function of cavity size from $(1\times1)a_0^2$ to $(1\times12)a_0^2$. Such a structure is analogous to the two-dimensional planar-mirror resonator. It is constructed by adding rods to a 5-(1)-5 QW structure from both sides. As expected, the measured linewidth becomes narrower as cavity size is reduced. Nonetheless, only part of the narrowing may be attributed to the reduction in loss through the sides since the simple picture that EM waves were being bounced back and forth between just two interfaces is no longer valid. Additionally, 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.

The size dependence of resonant frequency seen in Fig. 4 is consistent with the behavior of a two-dimensional resonator.[13] For a perfect 2D resonator, the frequency of the resonant modes is given by $2\pi\,((f/c))^2=(k_x^2+k_y^2)$, where $k_x=(p\pi/d_x)$, $k_y=(q\pi/d_y)$ are wave vectors for the standing wave, d_x, d_y are the size of the cavity, and p,q are positive integers. In our case, we approximate $d_x=(1+\alpha)a_0$ and $d_y=m(1+\beta)a_0$ for a $(1\times m)$ QB cavity. Here, α and β are positive numbers that have been introduced to correct for the fact that the wave function of the resonant mode penetrates into the barrier. Thus, the effective cavity size should be increased by a corresponding amount. The fit is shown in Fig. 4 as a solid line using $\alpha=(0.5\pm0.1)$ and $\beta=(1.2\pm0.1)$ as fitting parameters. We comment that the effective cavity size is also frequency dependent and has not been taken into account in our model. A more comprehensive theoretical account is necessary for a critical comparison.

In summary, we have tested a series of photonic quantum well and quantum box structures fabricated from a two-dimensional square array of dielectric rods. We show that such a structure behaves as a high-Q resonant cavity of tunable mode frequency and mode linewidth. Through a proper optimization of PBG-structure parameters, including cavity size, barrier thickness, size of photonic band gap, and low loss dielectric materials, a cavity Q of 2.3×10^4 is achieved and of $0.5–1\times10^6$ is expected in the mm-wave spectral regime.

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[11] The Q value is related to the full width half power point, i.e., Γ, of the resonators Lorentzian response line shape (see Ref. 12) as: $Q=f/\Gamma$. Here, f is the resonant frequency.
[12] See, for example, A. Yariv, *Introduction to Optical Electronics* (McGraw-Hill, New York, 1976), p. 78, 79.
[13] See, for example, B. E. A. Saleh and M. C. Teich, *Fundamentals of Photonics* (Wiley, New York, 1991), p. 323.