Transmission Characteristics of Metallodielectric Photonic Crystals and Resonators

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***Abstract*—K_u band Fabry–Perot type resonances have been observed in the stop band of a metallodielectric photonic crystal by transmission measurements at microwave frequencies. The metallodielectric photonic crystal has a face centered cubic Bravais lattice structure with a lattice constant of 15 mm. Metallic spheres with 6.35 mm diameter are placed at the lattice sites. The metallodielectric photonic crystal displayed a directional bandgap with a lower band edge of 13.0 GHz, an upper band edge of 21.5 GHz and a center frequency of 17.25 GHz, corresponding to a stop bandwidth center frequency ratio of 50%. The maximum rejection at the band center is 35 dB, corresponding to a 7 dB per unit cell rejection ratio. The Fabry–Perot type resonance in the K_u band has a quality factor of 200, with a maximum transmission peak of −5 dB.**

***Index Terms*—Photonic band gap materials, photonic crystals, resonators.**

PHOTONIC bandgap (PBG) materials have recently attracted much attention from the photonics community [1], [2]. PBG materials are constructed by spatially patterning the permittivity (ε) of a medium in a periodic way. Such a medium exhibits photonic stop bands, i.e., PBGs, for a certain range of frequencies of the electromagnetic (EM) spectrum [3]. Photons with frequencies lying in the PBG cannot propagate in the medium, thereby enabling the control of the transmission characteristics of the medium.

Despite the technological challenges, three-dimensional (3-D) semiconductor photonic crystals have been recently realized in the optical and near-infrared (near-IR) regime [4]. Metallodielectric photonic crystals have also been fabricated in the far-IR regime [5]. In addition to the visible and IR, photonic crystals have also found applications in the microwave and millimeter wave regime such as high directivity antennas [6], [7] high quality resonators [8], accelerator cavities [9], as well as high power [10] and broadband [11] reflectors. Dielectric photonic crystals composed of spherical [12] and nonspherical [13], [14] atoms have been investigated in the microwave regime. The stop bandwidth of these photonic crystals can be enhanced using metals, which have large imaginary refractive indices at microwave and millimeter frequencies.

Metallodielectric photonic crystals composed of flat atom metal elements [15], metallic island elements [16], wire meshes [17], and spheres have already been investigated experimentally [18] and theoretically [19] at microwave frequencies. However, some applications require the inclusion of defects in the metallic photonic crystal to select a transmitting state within the stop band [20]. These defects can be zero-dimensional for cavity [21], one-dimensional for waveguide [22], and two-dimensional for Fabry–Perot type resonator applications.

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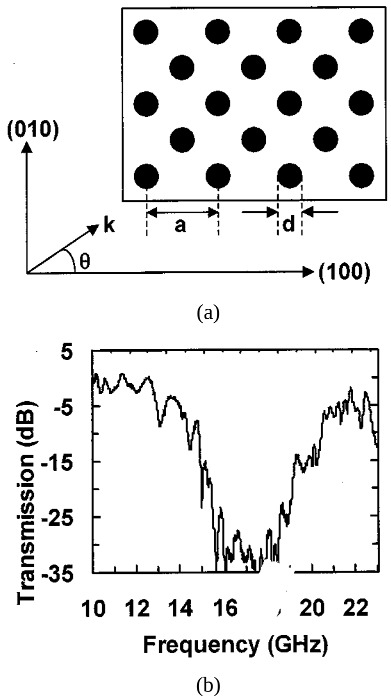

Fig. 1. (a) Top view of the (001) oriented face of the metallodielectric photonic crystal; (b) normal 0° (100) incidence transmission through the metallodielectric photonic crystal.

The metallodielectric photonic crystal with the resonator geometry can be applied to microwave tubes, such as klystrons, magnetrons, cross-field amplifiers (CFAs), and traveling wave tubes (TWTs) [23]. Additional resonator applications may include microwave spectrum analyzers or microwave amplification by stimulated emission of radiation (MASER) cavities.

In the experiments, we have investigated a 3-D metallodielectric photonic crystal in the microwave regime. The metallodielectric photonic crystal has an fcc Bravais lattice composed of steel spheres, with diameter $\mathrm{d} = 6.35$ mm. The lattice was formed along the (100) direction by stacking alternating layers of steel spheres. One layer consists of spheres packed as shown in Fig. 1(a), which depicts the (001) plane (top view) of the metallodielectric photonic crystal. The layer above and below that layer has the same layout, but they are offset by half a lattice constant in both horizontal directions. Our metallodielectric pho-

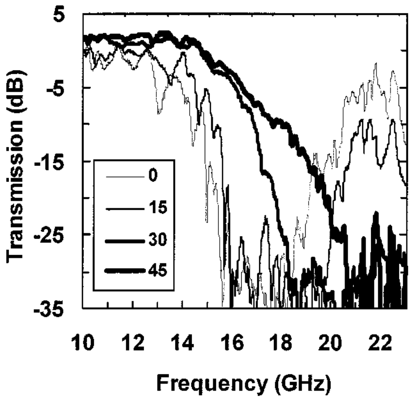

Fig. 2. Normal 0° (100) [very thin line], 15° [thin line], 30° [thick line], 45° (110) [very thick line] incidence transmission through the metallodielectric photonic crystal.

tonic crystal consisted of 11 layers or five unit cells. The lattice constant was $\mathbf{a} = 15$ mm, corresponding to a packing fraction of $\mathbf{f} = 0.16$. The supporting dielectric material was air doped polystyrene with a refractive index of 1.16.

After assembly, the microwave transmission through the metallodielectric photonic crystal was measured from 9.5 to 24.5 GHz with a Hewlett-Packard 8510C network analyzer. Standard gain horn antennas were used to transmit and receive EM radiation. Surroundings of the test setup was covered with absorbers to build an anechoic chamber resulting in a sensitivity of 85 dB. The transmission calibration was performed using the standard gain horn antennas, before placing the photonic crystal in the microwave beam.

We first measured the transmission properties of the metallodielectric photonic crystal without the Fabry–Perot type cavity resonator. Fig. 1(b) shows the transmission spectrum through the metallodielectric photonic crystal along the (100) crystal direction. The lower edge of the stop band starts at 13.0 GHz. The center frequency for the stop band is at 17.25 GHz, which compares favorably with the normal ($\boldsymbol{\theta} = 0°$) incidence Bragg condition frequency $\boldsymbol{\nu}_{\mathrm{Bragg}} = \mathbf{c}/\mathbf{2an}\cos(\boldsymbol{\theta})$, where $\mathbf{c}$ is the speed of light in vacuum, $\mathbf{n}$ is the refractive index of the metallodielectric medium and $\boldsymbol{\theta}$ is the angle between the (100) crystal direction and the $\mathbf{k}$-vector of the incident EM wave. The upper edge of the stopband is at 21.5 GHz. Therefore, the width of the stopband is 50% of the center frequency, which makes our metallodielectric photonic crystal suitable for microwave applications. Additionally, the upper edge and the lower edge of the stopband compare favorably to the frequencies estimated using the calculations of [19]. Ignoring the oscillations, the maximum rejection at the band center is 35 dB, corresponding to a rejection of 7 dB per unit cell. The transmission below and above the stop band is unity, which is remarkable considering that a metallic surface would have reflected 99.97% of the incident radiation in the given microwave frequency range.

We also studied the effect of the incidence angle on the transmission spectra of the fcc metallodielectric photonic crystal. Fig. 2 shows the transmission spectrum through the metallodielectric photonic crystal along $\boldsymbol{\theta} = 0°$, 15°, 30° and 45°. The center frequency for the stop band is at 17.25, 18.25, 20.1, and 24.3 GHz for the $\boldsymbol{\theta} = 0°$, 15°, 30°, and 45°, respectively.

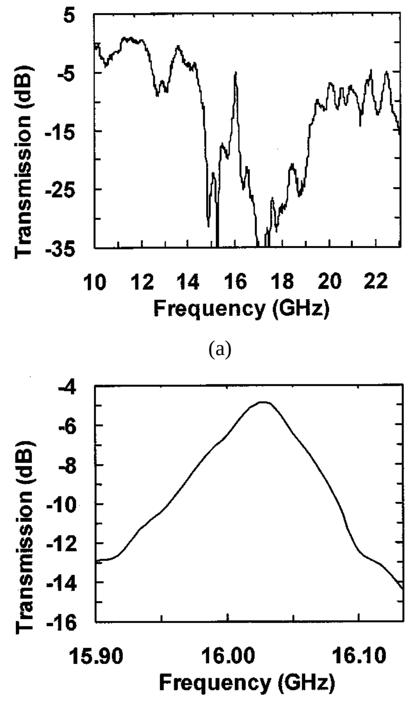

Fig. 3. (a) Normal 0° (100) incidence transmission through the metallodielectric fcc photonic crystal with the gap in the middle, (b) expanded frequency scale of the spectrum of Fig. 3(a).

The PBG shifts toward higher frequencies as expected from the Bragg condition on the center frequency. In addition to the stopband shifting to the blue with increasing incidence angle, the stopband also broadens. This behavior has also been observed in the theoretical band calculations [19]. This is due to more wavelengths satisfying the Bragg condition in those specific crystal directions. Additionally, there is a smearing of the red band edge as the angle is increased. This behavior has also been observed previously both experimentally [15] and theoretically [24] and is due to the Bragg condition.

We later measured the transmission properties of the fcc metallodielectric photonic crystal with the Fabry–Perot type cavity resonator. The Fabry–Perot type cavity resonator is formed by separating the photonic crystal into two separate identical blocks each consisting of five layers, where each five layer stack acts like the mirror of a Fabry–Perot cavity resonator. The separation distance is set to be $\mathbf{L} = 17.5$ mm between the 2 parts (mirrors) of the metallodielectric photonic crystal. Fig. 3(a) shows the transmission spectrum of the metallodielectric photonic crystal at low spectral resolution and along (100) crystal direction. The spectrum in Fig. 3(a) is very similar to the full metallodielectric photonic crystal spectrum of Fig. 1(b), except the Fabry–Perot type mode at frequency $\boldsymbol{\nu}_{\mathbf{FP}} = 16.02$ GHz.

Fig. 3(b) shows the transmission spectrum of the metallodielectric photonic crystal at high spectral resolution for the (100) crystal direction. The Fabry–Perot type mode at frequency $\boldsymbol{\nu}_{\mathbf{FP}} = 16.02$ GHz, has a linewidth of $\boldsymbol{\Delta\nu}_{\mathbf{FP}} = 0.08$ GHz and a quality factor of $\mathbf{Q} = \boldsymbol{\nu}_{\mathbf{FP}}/\boldsymbol{\Delta}_{\mathbf{FP}} = 200$. The Fabry–Perot type mode frequency of 16.02 GHz compares favorably with the Fabry–Perot resonance condition of $\boldsymbol{\nu}_{\mathbf{FP}} = \mathbf{c}[\mathbf{2}\boldsymbol{\pi}\mathbf{m} - \boldsymbol{\varphi}]/\mathbf{4}\boldsymbol{\pi}\mathbf{L}$, where $\mathbf{m}$ is the mode number, φ is the total reflection phase of the two mirrors and $\mathbf{L}$ is the separation distance [25]. From the frequency of the Fabry–Perot type resonance, the mode number is found to be $\mathbf{m} = 2$ and the total reflection phase of the two mirrors $\varphi = 47^{\circ}$.

In conclusion, a Fabry–Perot type cavity resonance has been observed in the stop band of a metallodielectric photonic crystal by transmission measurements at microwave frequencies. The metallodielectric photonic crystal has an fcc Bravais lattice structure, with metallic spheres at the lattice sites. Our sample having a cubic lattice constant of 15 mm with 6.35 mm diameter steel spheres at each atomic core displayed a center frequency of 17.25 GHz, a lower band edge of 13.0 GHz, upper band edge of 20.5 GHz, and a stop bandwidth center frequency ratio of 50%. The maximum rejection at the band center is 35 dB. The rejection per unit cell is 7 dB. The Fabry–Perot type resonance observed at 16 GHz has a linewidth of 0.08 GHz and a quality factor of 200, with a maximum transmission peak value of -5 dB.

By choosing the propagation direction perpendicular to the gap and with the appropriate tuning mechanism, the Fabry–Perot resonator geometry can be used as a microwave spectrum analyzer or, alternatively, a MASER cavity. However, by choosing the propagation direction parallel to the gap, we obtain the waveguide geometry [26], which can be used to guide the microwave in the photonic crystal. The inclusion of a gap defect in the metallodielectric photonic crystal provides further physical insight on the behavior of the electromagnetic modes of this type of photonic crystal.

More realistic applications for the metallodielectric photonic crystal can be envisioned in microwave tubes, such as magnetrons, klystrons, cross-field amplifiers (CFAs) and traveling wave tubes (TWTs). These microwave tube devices are still in use today, mostly in satellite communication and radio detection and ranging (RADAR) applications.

The periodic coupled cavity structure already present in the TWT's can be improved by the incorporation of the metallodielectric photonic crystal. The Fabry–Perot resonator geometry may provide additional radio frequency (RF) selectivity for the input and output cavity of the klystron. The incorporation of the metallodielectric photonic crystal in the anode of the magnetron, or the slow wave structure (SWS) of the CFA could increase the frequency selectivity of these microwave devices. Additionally, the fabrication of these microwave devices using the metallodielectric photonic crystal may improve the packaging weight, size, thermal management and lower cost.

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