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Gallant, A.J. and Kaliteevski, M.A. and Wood, D. and Petty, M.C. and Abram, R.A. and Brand, S. and Swift, G.P. and Zeze, D.A. and Chamberlain, J.M. (2007) 'Passband filters for terahertz radiation based on dual metallic photonic structures.', Applied physics letters., 91 (16). 161115 .

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http://dx.doi.org/10.1063/1.2800381

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APPLIED PHYSICS LETTERS **91**, 161115 (2007)

# Passband filters for terahertz radiation based on dual metallic photonic structures

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(Received 5 July 2007; accepted 28 September 2007; published online 18 October 2007)

This paper reports on the development of two-dimensional metallic microstructures for the filtering of terahertz radiation. These structures are fabricated using ultraviolet-based processing of thick SU8 resist. This micromachining technique enables the array patterns, dimensions, and consequently the filter characteristics to be readily defined. In particular, we demonstrate that a filter with an isolated near-square-shaped passband can be realized on the basis of a combination of two different metallic photonic arrays of optimized design. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2800381]

The terahertz region of the electromagnetic spectrum (300 GHz to 10 THz) has attracted considerable attention in the recent literature, but when compared to the optical and microwave regions, it remains relatively unexplored. The so-called "terahertz gap" has now been bridged through the development of efficient generation and detection systems,[1] and applications are rapidly emerging in the generation, filtering,[2] and imaging and spectroscopy[3] of terahertz radiation[4] for biomedical, security, and manufacturing control. However, the continued development of terahertz-based systems is reliant upon the implementation of techniques to guide, focus, and filter the radiation effectively.

Spectral filters are an important element of most systems which manipulate radiation, and it has recently been demonstrated that metallic photonic crystals of appropriate dimensions possess passbands[5] in the terahertz region, and the positions and widths of the passbands are defined by the geometry of the photonic crystal. Experimental studies of the transmission of terahertz radiation in such structures[6] have confirmed the theoretical results showing that metallic photonic crystals (pillar array) can have a maximum transmission close to unity within some bands. However, an ideal spectral filter should allow the complete transmission of radiation for a particular frequency range and zero transmission outside that range. In other words, it should have a single passband.

In this paper, we demonstrate that more complex structures, based on the metallic pillar forest, can isolate, and even sharpen, specific pass-bands, and hence provide filtering technology in a region where traditional electrical techniques are difficult to implement. Specifically, we have fabricated by micromachining dual structures that are combinations of two two-dimensional (2D) square-lattice photonic crystals formed by metallic pillars, as shown in Fig. 1, and have measured and modeled their terahertz transmission properties.

Micromachining is the fabrication of three dimensional surfaces and structures on the submicron to millimeter scale, and is therefore well suited to the fabrication of terahertz artificial materials (where 1 THz≡300 $\mu$m). Both surface and bulk techniques are well established for the fabrication of three dimensional topologies at micron resolution. The processes are adapted from those used in the integrated circuit industry and therefore can be readily implemented in production environments.

The fabrication of high aspect ratio pillar arrays is achieved via an SU8 fabrication process. First, an optically opaque metal, such as gold, is evaporated onto a glass wafer. The metal is then patterned with holes where the SU8 should remain to form the pillars. Then, a layer of SU8-50 is drop dispensed onto the glass wafer and confined by an *o*-ring during its soft bake stage, which is performed for 5 h at 120 °C. After cooling, the wafer is flipped over and exposed with broadband UV in order to partially crosslink the SU8. Full crosslinking is achieved after a postexposure bake of 1 h at 120 °C. The wafer is then developed in Microposit EC solvent and air dried to release the micropillar arrays. Using this technique, pillars can readily be fabricated with diameters as small as 40 $\mu$m and heights in excess of 1 mm. However, smaller pillar diameters (i.e., smaller apertures in the gold layer) restrict the incident UV and act to limit the final pillar height. The SU8 is fairly transparent to the incident terahertz radiation, and therefore it is necessary to sput-

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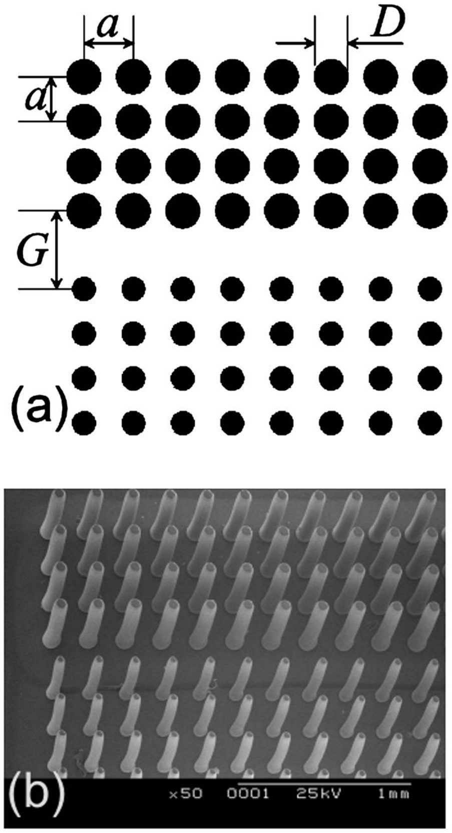

FIG. 1. (a) Schematic view of a dual structure made by combining two 2D square-lattice photonic crystals formed by metallic pillars. (b) Scanning electron microscopy image of the structure.

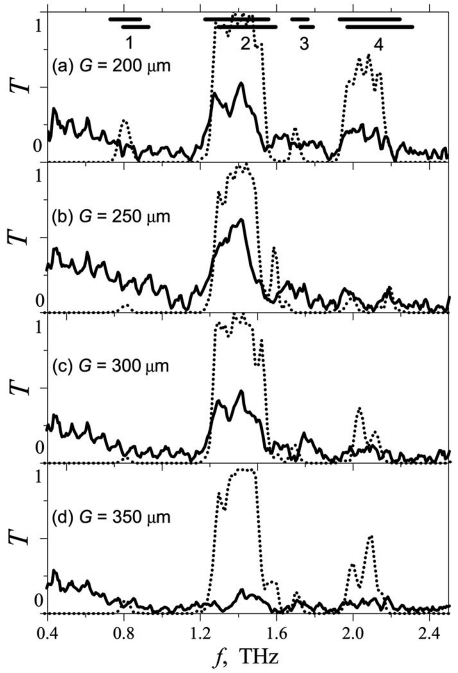

FIG. 2. Transmission spectra for filters formed by two 2D square-lattice-based arrays consisting of four lines of metallic rods with a period of 200 $\mu$m and with rod diameters $D=60$ $\mu$m and $D=70$ $\mu$m, respectively. The gap between the arrays are: (a) $G=200$ $\mu$m; (b) $G=250$ $\mu$m; (c) $G=300$ $\mu$m; (d) $G=350$ $\mu$m. Experimental results are shown by solid lines and finite difference time domain numerical modeling results by dotted lines. The horizontal bars in Fig. 2(a) show the positions of the passbands for infinite periodic crystals with rod diameters $D=60$ $\mu$m (upper bars) and $D=70$ $\mu$m (lower bars).

ter coat the pillars with gold (approximately 0.3 $\mu$m). The pillars can effectively be treated as metal rods because the gold layer is much thicker than the skin depth. The fabrication technique is very adaptable since complex pillar arrays can be created by simply changing the photolithographic mask that defines the metal pattern on the glass substrate.

The terahertz transmission measurements were performed in a terahertz time domain spectroscopy system which has a usable bandwidth of approximately 3 THz. A Ti:sapphire laser produced a 600 mW pulse of 20 fs duration with a repetition rate of 76 MHz. This was separated into a terahertz-generating beam and a gating beam with a 70:30 beam splitter. The generating beam was focused onto an low temperature grown GaAs photoconductive strip line emitter which was dc biased to 250 V. Parabolic mirrors were used to focus the terahertz signal onto the pillar array sample.

The beam diameter was approximately 1 mm and comparable to the height of the pillars. At lower frequencies (hundreds of gigahertz), the beam was more divergent and could therefore pass over the top of the pillars, leading to some unfiltered leakage. The gating and the terahertz beam were focused onto a 1 mm thick ZnTe electro-optic crystal, which, in conjunction with a balanced detector, were used to detect the transmitted terahertz radiation. A delay line for the generation signal allowed the electric field of the terahertz pulse to be scanned in the time domain. A fast Fourier transform was then used to obtain a frequency spectrum. The system provided a usable bandwidth of approximately 3 THz.

For a frequency interval corresponding to a passband, the pillar array is transparent to the incident radiation, whereas for frequencies outside a passband, the radiation is reflected. The widths and positions of the passbands are defined by the geometrical parameters of the system. For a photonic crystal with a square lattice formed by an array of parallel pillars, the relevant parameters are the period of the structure $a$ and the pillar diameter $D$. If one combines two different pillar arrays, as shown in Fig. 1, then the resulting filter is expected to be transparent in the frequency interval, which is formed by the overlap of the passband of the individual pillar arrays. The resulting transmission will also depend on the separation $G$ between the two pillar arrays [see Fig. 1(a)].

Figure 2 shows calculated[7] and measured transmission spectra of various combined filters made from two square lattice pillar arrays with pillar diameters $D=60$ $\mu$m and $D=70$ $\mu$m, respectively, and a uniform height of 1 mm. The period of all the arrays is $a=200$ $\mu$m, but different values of the gap $G$ are considered. The horizontal bars in Fig. 2(a) show the passbands for individual pillar arrays; the passbands for the different dual arrays are centered at approximately 1.4 THz. Figure 2(a) shows the spectra for the combined filters with a gap $G=a=200$ $\mu$m, for which the crystalline lattice is preserved. In the calculated spectrum, one can see that the transmission band corresponds to the overlap of the passbands of the individual pillar arrays. For the first and third bands, the overlap is small, the transmission for the bands is less than that for the second band, and the transmission of the dual structure can be seen as small peaks in the calculated spectrum. In contrast, for the second

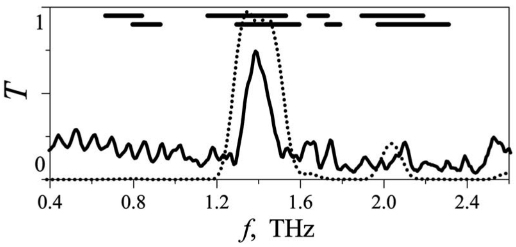

FIG. 3. Transmission spectra for a combined filter formed by two pillar arrays with a period of 200 $\mu$m, containing metal rods with diameters $D=50$ $\mu$m and $D=70$ $\mu$m, respectively, and separated by a gap $G=250$ $\mu$m. The vertical length of the pillar is 1 mm. The experimental spectrum is shown by the solid line and the numerical modeling results by the dotted line. The horizontal bars show the positions of the passbands for infinite periodic crystals with rod diameters $D=50$ $\mu$m (upper bars) and $D=70$ $\mu$m (lower bars).

and fourth bands, the overlap is substantial and one can see wide passbands, with a predicted transmission coefficient close to unity for the second band. In the experimental spectrum, the second and fourth bands are well pronounced, but the value of the transmission coefficient is smaller due to out-of-plane scattering. An increase of the gap *G* to 250 $\mu$m [Fig. 2(b)] leads to the suppression of all except for the second band in the calculated spectrum, and the experimental spectrum also shows similar behavior. In the experimental spectra for the cases $G=250$ $\mu$m and $G=300$ $\mu$m, one can see a pronounced second band, but the value of the transmission coefficient decreases with increasing gap due to out-of-plane scattering in the gap region, and when the gap becomes as large as $G=350$ $\mu$m [Fig. 2(d)], the transmission band in the experimental spectrum disappears.

Suppression of the transmission band by varying the gap size can be explained using the following arguments. An overlap of the passbands in the individual pillar arrays is necessary for transmission, but it is also necessary for a Bloch mode of the electromagnetic field in the first individual array to excite a Bloch mode in the second array. In photonic crystals with different pillar diameters, the spatial structure of the Bloch electromagnetic modes for the same frequency is different,[8] and for a specific range of the gap sizes, the spatial structure of the field in the gap, induced by the Bloch mode in the first array, does not excite Bloch modes in the second array.

By optimizing the parameters of the combined filters, one can obtain a transmission spectrum with a single, isolated, and nearly square-shaped passband. Figure 3 shows the transmission spectra of combined filters comprising two pillar arrays with a period of 200 $\mu$m separated by a gap $G=300$ $\mu$m. Both the experimental and calculated spectra show an isolated passband centered at 1.4 THz with a width of about 0.3 THz.

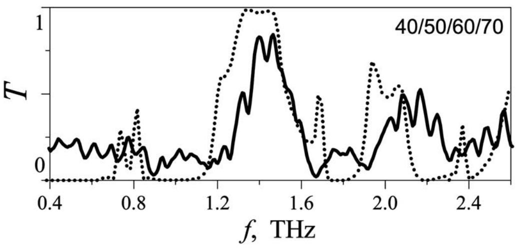

FIG. 4. Transmission spectra through the structure formed by four layers of pillars with rod diameters of 40, 50, 60, and 70 $\mu$m, respectively. The rod center separation (period) is 200 $\mu$m. Results of experimental measurements are shown by a solid line and numerical modeling by a dotted line.

For comparison, Fig. 4 shows the transmission spectra of a graded structure consisting of four rows of pillars with diameters of 40, 50, 60, and 70 $\mu$m. One can see that the structure of the spectra is similar to that of an individual pillar array[6] with several passbands. This example illustrates that to obtain a well defined passband, one should use pillar arrays with enough layers to form a Bloch wave.

We have demonstrated passbands filters for terahertz radiation based on the combination of two individual pillar arrays separated by a gap. The resultant passband is characterized by a virtually flat-topped transmission spectrum.

The authors wish to acknowledge the support of the Engineering and Physical Science Research Council of the United Kingdom (Grant No. EP/C534263).

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