Multiband Infrared Frequency Selective Surfaces

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ABSTRACT

This paper describes the design and fabrication of multiband infrared frequency selective surfaces (FSSs) that consist of self-similar fractal cross dipole metallic elements patterned on flexible dielectric substrates. Two transmission stopbands centered at 6.4 THz (–15.3 dB) and 17.5 THz (-6.2 dB) were measured on FSSs with primary and secondary cross elements that are 17 μm and 7 μm long and 1 μm wide. These properties correspond well to those predicted by a periodic method of moments model that was used to formulate electromagnetic scattering from this FSS. Future work will include modulating passband frequencies through field-controlled modulations of the physical properties of the substrate.

INTRODUCTION

A frequency selective surface (FSS) is a two dimensional periodic array of metallic patches or aperture elements on a dielectric substrate. Fractal elements have been used at the microwave scale to produce FSSs with transmission and reflection spectra insensitive to angle of incidence and wave polarization.[1] By properly manipulating the shape and dimensions of the metallic elements, strong stopbands and passbands in the FSS spectra can be achieved. While FSSs were first used for signal filtering in the microwave region, the complete scalability of the theory allows a wide variety of infrared filtering devices to be created through microfabrication.[2] While it is more common for infrared filtering devices to be made using dielectric multilayers, metallic FSSs offer several advantages for such an application. One primary advantage of FSSs over dielectric multilayers is that multiple resonances (stopbands in the transmission spectrum) can be achieved with a single layer of elements, whereas a dielectric device would require several multilayer structures to achieve a multiband response.[3] This two-dimensional structure produces a multiband response with reduced cost and fabrication time by exploiting the self-similarity of fractal structures.[1] We report here on the design, modeling, and fabrication of an FSS on a thin, transmissive dielectric substrate, with Stage 2 cross dipole fractal elements exhibiting dual stopbands of –15.3 dB and –6.2 dB in the far infrared.

DESIGN

The Stage 2 cross dipole fractals, which serve as the metallic elements of this FSS, exhibit two resonances corresponding to the two iterations of the fractal structure. A drawing of the cross dipole fractal structure is shown in Figure 1a. The length of the primary crosses in each element (there is one primary cross per element) determines to first order the position of the lower frequency (primary) resonance. The length of the secondary crosses (there are four secondary crosses per element) determines the position of the higher frequency (secondary) resonance. Figure 1b shows the modeled ideal dual band response for structures of the geometry shown in Figure 1a. The position in the frequency domain of the two bands can be completely controlled by the scale of the metallic elements, while the secondary band can be moved relative to the primary band by scaling only the secondary cross dimensions of the fractal structure. Figure 1c shows the cross dipole fractal structures with smaller secondary crosses, while Figure 1d shows the corresponding modeled ideal transmission spectrum with a blue-shifted secondary band.

The fundamental multiband responses of the fractal cross dipole structure have been well studied for applications at microwave frequencies. For this infrared application, modeling was used to gain a better understanding of design parameters. There are numerous methods that have been introduced for analyzing periodic structures. A simple method for analyzing FSSs is the equivalent circuit model.[4] This method models metal patches in the cell geometry of the FSS as either inductive or capacitive components on a transmission line. Thus, for simple geometries, the frequency response can be judged based on the components of the geometry. However, for more complex geometries the frequency response may not be as intuitive. A periodic method of moments (PMM) model is used to formulate the electromagnetic scattering from the FSSs in this paper. Floquet's theorem is applied to the formulation of the integral equation to account for the periodic boundary conditions of the unit cell.[4,5] The PMM code used to analyze these FSSs includes the ability to model substrates and superstrates surrounding the FSS metal screen as well as multiple arbitrary FSS screen geometries. The FSS screens may be modeled as either perfectly conducting or as resistive patches. Loss may also be added to any of the dielectric layers.

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One design parameter studied was the spacing between elements in the FSS periodic array. This spacing affects the electromagnetic coupling between elements, with a greater impact on the secondary crosses of the Stage 2 fractal. Also investigated by the modeling was the sensitivity of the secondary resonant response to material parameters such as substrate thickness, dielectric properties of the substrate, and loss in the metallic elements.

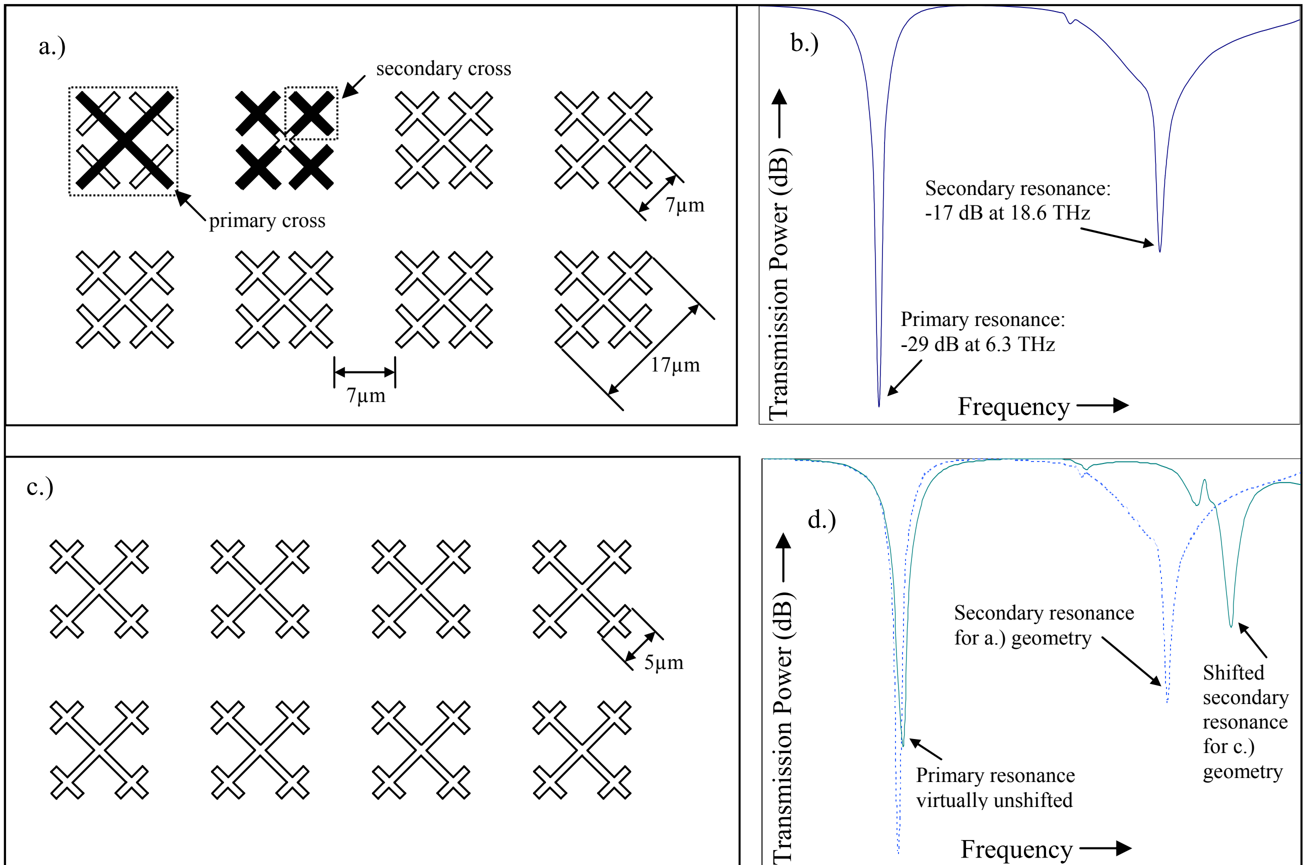

Fig. 1 a.) is a drawing of a partial array of fractal cross dipole elements of the same dimensions reported on here. b.) is an example of an ideal transmission spectrum of such an FSS. The resonance at lower frequency is due to the primary arm of the fractal cross dipole, while the resonance at higher frequency is due to the secondary arm. c.) is a drawing of a partial array of fractal cross dipole elements with a shortened secondary cross. The solid green curve in d.) is an example of an ideal transmission spectrum for an FSS with dimensions from c.); the dashed curve is the data from b.) replicated for comparison. Note that the secondary resonance is shifted to higher frequency due to the shortening of the secondary cross dimension, demonstrating the scalability of individual bands in addition to the scalability of the entire structure. The primary band is shifted only slightly due to loading effects.

The characteristics of single cross dipoles, which include only the primary cross shown in Figure 1a, have been studied in the infrared,[2] and these single cross dipole FSSs were also included in our set of fabricated samples. These structures exhibit a single band response, at a frequency similar to that of the corresponding primary resonance of the multiband structure. The primary multiband response is slightly redshifted from the single band response due to the crossbars forming the secondary cross in the fractal structure. These secondary crossbars create a loading effect on the primary cross, making its dimensions appear electrically longer, and thus it is resonant at a longer wavelength.

FABRICATION

Frequency selective surfaces with dimensions and spacing shown in Figure 1a were fabricated on two different types of thin, transmissive insulating substrates. Modeling results indicated that the primary and secondary resonances are sharper and deeper when the substrate thickness is less than 1/20 of the resonant wavelength. Of the two substrates fabricated, one was thinner than this guideline, while the other substrate was thicker. For the thin substrate case, silicon nitride was chosen as the substrate material because it can be easily deposited in a uniform thin film, and is transmissive in the far infrared. To fabricate the FSS on a thin substrate, a 200 nm layer of silicon nitride was deposited on both sides of a silicon wafer via low-

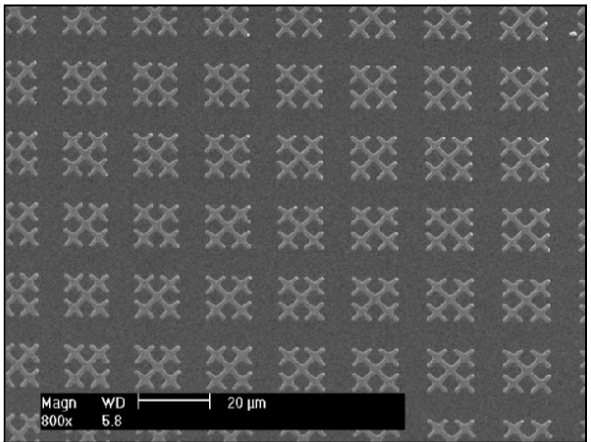

Fig. 2 An SEM image of the Stage 2 fractal cross dipole FSS elements. The primary cross length is 17 µm and secondary cross length is 7 µm.

pressure chemical vapor deposition (LPCVD). The FSS features were fabricated by contact lithography and thermal deposition of a 75 nm aluminum layer on top of this nitride layer. After liftoff, the silicon nitride with metallic features was separated from the silicon wafer at the sample area for characterization. A 2x5 mm^2 window of silicon nitride directly under the FSS array was removed from the backside of the wafer via reactive ion etching (RIE) with carbon tetrafluoride (CF_4) gas. Using the remaining silicon nitride on the backside of the wafer as mask, a 2x5 mm^2 window was etched through the silicon wafer using the potassium hydroxide (KOH) meniscus interface etching technique.[6] The result was a membrane of silicon nitride with 200 nm thickness suspended across the silicon wafer aperture, with FSS metallic elements on top of the membrane.

A FSS with a thicker, mechanically flexible substrate was also fabricated. This substrate was a polyimide (DuPont PI2574) film with a thickness of 4 µm, which was spun onto a silicon wafer and cured. The metallic features were patterned on top of the substrate by standard contact lithography. After metal deposition and liftoff identical to that described above, the polyimide film with metal features was removed from the silicon wafer for characterization. A portion of the FSS is shown in the scanning electron microscope (SEM) image in Figure 2.

CHARACTERIZATION

The transmissive properties of the FSSs were characterized by Fourier Transform Infrared (FTIR) Spectroscopy, using a Bruker Optics *Equinox 55* model FTIR. Spectral data was taken from 1.5-24 THz (12.5-200 microns) using an incoherent unpolarized light source. The spectral data shown here is the result of normalizing the spectrum of the metallic elements and substrate to the spectrum of a blank substrate of the same material and thickness. Doing so reduces the presence of absorption peaks from the substrate in the transmission spectrum of the FSS.

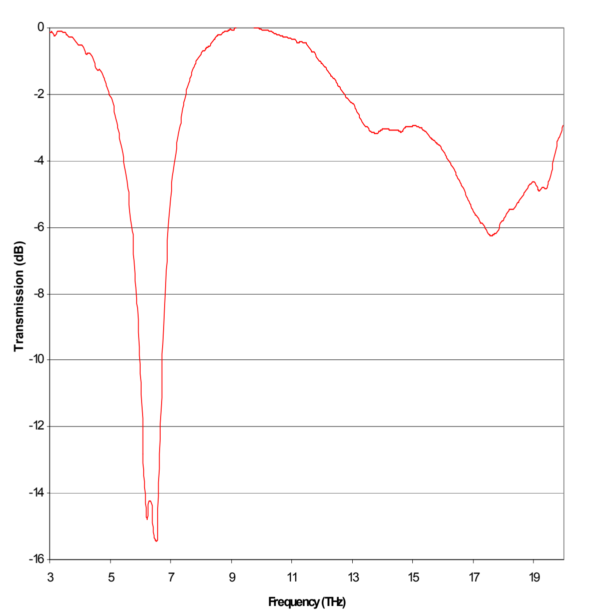

Fig. 3 Measured transmission spectrum of a FSS on a 200 nm silicon nitride substrate with primary and secondary cross lengths of 17 and 7 µm respectively. The primary resonance is –15.3 dB centered at 6.4 GHz while the secondary resonance is –6.2 dB centered at 17.5 GHz.

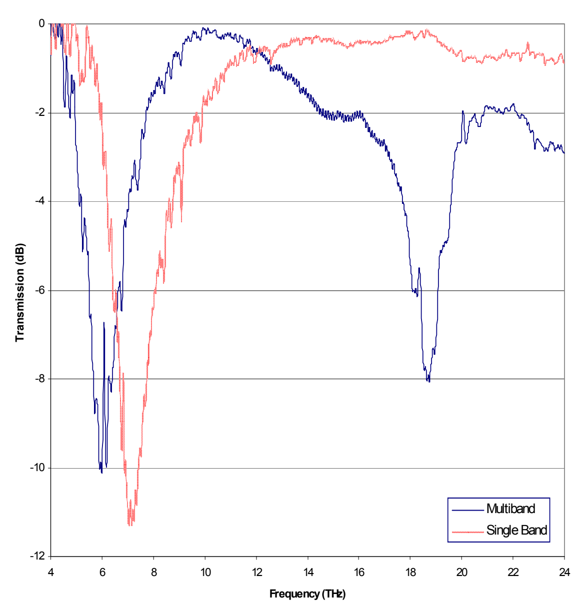

Fig. 4 Comparison of multiband and single band transmission spectra of cross dipole FSSs with 4 µm polyimide substrate. The primary resonance of the multiband FSS is shifted to a lower frequency than the single band resonance despite identical dimensions. This is because the crossbars of the secondary cross dipoles in the fractal case load the primary crosses, making them electrically longer than their physical size.

Figure 3 shows the transmission spectrum of the dual band FSS with a primary cross length of 17 µm and a secondary cross length of 7 µm. This FSS is on a 200 nm silicon nitride substrate, and the spectrum shown is normalized to a blank silicon nitride substrate of similar thickness. The primary resonance has a loss of -15.3 dB at 6.4 THz, and the secondary resonance has a loss of -6.2 dB at 17.5 THz. The secondary resonance is broader and less deep than the primary resonance due to the loss in the substrate material, an effect that is elucidated by the modeling and will be discussed in the following section.

Figure 4 shows the transmission spectra of both the dual band FSS with the same dimensions described above and the single band (single cross with a 17 µm length) FSS. These two FSSs are on 4 µm polyimide substrates, and the spectra are again normalized to a blank substrate. The primary resonance of the multiband fractal structure (6.0 THz) is redshifted from the resonance of the single band structure (7.0 THz), due to the loading effects of the secondary crossbar as predicted by the theory discussed earlier.

MODEL AND EXPERIMENT COMPARISON

The measured transmission spectra of the FSSs for all studied substrate cases exhibited secondary resonances which were significantly broader and less deep than those modeled in the ideal case of no substrate loss. However, when dielectric loss is added to the model, both the primary and secondary resonance become less deep, while the secondary resonance broadens considerably. This effect is shown in Figure 5, which compares three different simulated cases of the multiband FSS on a silicon nitride substrate. The first case considers the dielectric to be lossless; the second case includes a small amount of loss, adding an imaginary component of 0.1 to the effective dielectric constant. The third simulation has a larger loss, with an imaginary component of 1 added to the effective dielectric constant.

When the measured data is compared to the simulated transmission spectrum, the model provides a good fit for the experimental results when the simulation considers the effective dielectric constant to be 4 - 1j. Figure 6 compares the measured data of the FSS having primary and secondary cross lengths of 17 and 7 µm, respectively, on a silicon nitride substrate, to the simulated result for elements of the same dimension on a lossy silicon nitride substrate. The primary resonances of the model and experiment agree well with each other. The secondary resonances exhibit comparable broadness and depth, but the minimum of the experimental curve is shifted to a slightly lower frequency than is predicted by the model. This could be due to small inconsistencies between the actual structure dimensions and the structure dimensions in the model. Because the model input file is pixilated with limited resolution, the precision of the defined structure size (both line length and line width) is somewhat limited as well. This has a greater impact on the secondary cross, as the smaller size of that cross means a greater percent change for a given dimensional uncertainty. Additionally, the lithography used to define the metallic features in fabrication does not produce perfectly squared corners, instead resulting in slightly rounded features as can be seen in Figure 2. The model does not account for these imperfections either, which could also help explain the difference in resonant frequency. Despite these limitations, the model and experiment appear to be in good agreement with one another.

Silicon nitride was the most effective substrate of the two in this study in terms of the transmission spectrum characteristics. While the broadening of the second resonance is present in the silicon nitride case shown in Fig. 6, the effect is even more pronounced when a thicker polyimide substrate is used. The modeling shows that a substrate on the order of several microns thick will exhibit spurious resonances in the far and mid infrared. These resonances

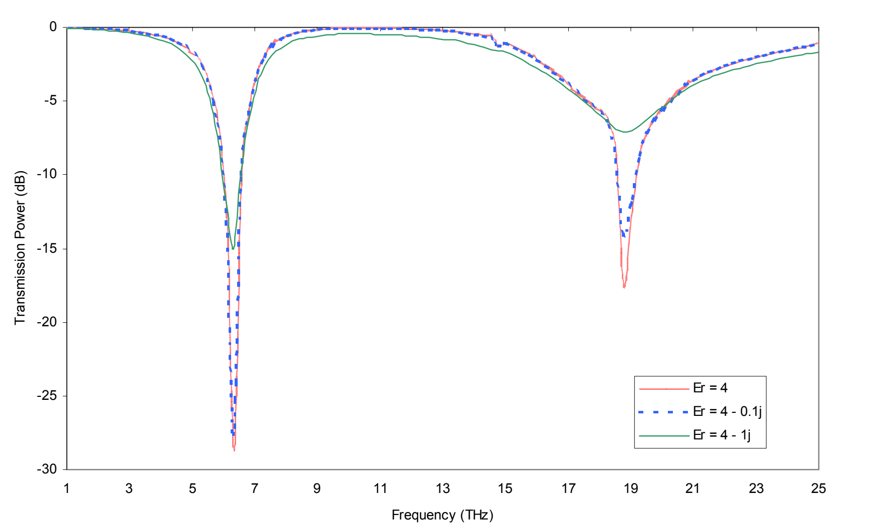

Fig. 5 A comparison of simulations with different amounts of dielectric loss. The dotted red line is the ideal case with no dielectric loss. The dashed blue line has a small amount of loss, while the solid green line has ten times the amount of loss as the second case. With added loss, the resonances lose depth, and the secondary resonance broadens significantly.

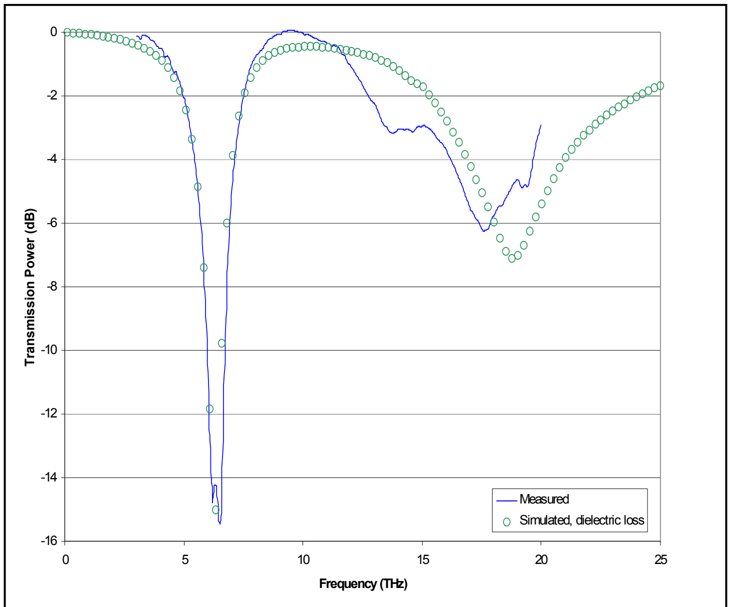

Fig. 6 A comparison of the measured transmission spectrum of the FSS on silicon nitride with the simulated transmission spectrum when the dielectric is modeled as lossy.

result from the coupling fields between the metallic elements forming standing waves between the boundaries in the dielectric media. A dielectric with loss can cause several of these spurious resonances to broaden and overlap one another as well as the secondary resonance, forming one broad, but shallow band. Simulations with a thinner polyimide layers show a significant reduction of this effect, and efforts are currently underway to fabricate thinner polyimide substrates.

An area of focus in future attempts to improve the multiband performance will be the enhancement of the depth and width of the secondary resonance. Reducing the substrate loss will be one point of emphasis, and modeling efforts have already suggested new fractal structure designs with improved secondary resonance characteristics. Efforts will also be made to demonstrate experimentally the characteristics of the reflection spectra of these FSSs. Modeling has already demonstrated that an FSS with a stopband in the transmission spectrum will have a passband resonance at the same frequency in its reflection spectrum, with effectively no transmission outside this band. Additionally, cross dipole fractal aperture elements can be patterned into a metal plane, giving the complementary structure of the FSSs reported on here. Modeling shows that such a complementary structure would have passbands at the resonant frequencies in the transmission spectrum, with no transmission outside the bands. Likewise, the complementary structure would exhibit stopbands in the reflection spectrum.

FUTURE WORK TOWARD TUNABILITY

The FSSs described here are already fully tunable at the design stage of the development process, but once fabricated, the devices have a static frequency response. Future efforts will involve making the FSSs tunable or reconfigurable in real time. The techniques currently under consideration for this task involve fabricating the FSS on a substrate that is either electrostrictive or has a variable index of refraction. Electrostrictive substrates could be stressed by an external field in the plane of the surface to vary the spacing between metallic elements of the FSS array.[7] Changing this spacing will alter the coupling between elements, and thus the frequency response of the surface, as described in the previous sections. Alternatively, a multilayer FSS with an electrostrictive substrate between layers could be compressed or expanded in the vertical dimension to vary the coupling between metal layers. Fabricating the FSS on a substrate with a variable index of refraction such as liquid crystal (LC) is another possibility for creating a tunable response. Ordering of the LC by an external field can change the index of refraction of the substrate from the index of the disordered state, thus moving the position of the resonant bands of the FSS. Finally, some polymer LCs have demonstrated a combination of electrostriction and variable index of refraction, which could provide better tuning capabilities than either technique alone.[8]

CONCLUSION

Multiband infrared FSSs have been modeled, fabricated, and characterized utilizing the self-similarity of fractal cross dipoles to achieve multiple stopbands in the transmission spectrum of a single layer device. The FSSs have been fabricated on a variety of thin, transmissive substrates. The single layer multiband FSS offers a lower cost and simpler fabrication alternative to multilayer FSS. Substrate properties such as dielectric loss have been investigated through modeling and used to explain the experimental results. Modeling efforts will continue to identify alternative fractal structures that could offer improved resonance depth and sharpness. Future research will also investigate the characteristics of the reflection spectrum, as well as the fabrication and characterization of the complementary structures. Real time tunability will be addressed through the use of electrostrictive and variable index substrates.

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REFERENCES

[1] D. H. Werner and S. Ganguly, IEEE Ant. Prop. Mag. **45**, 38 (2003)
[2] I. Puscasu *et. al.,* J. Vac. Sci. Technol. B **18**, 3578 (2000)
[3] J. D. Joannopoulos, R. D. Meade, and J. N. Winn, *Photonic Crystals* (Princeton University Press, Princeton, N.J., 1995)
[4] T. K. Wu, ed., *Frequency Selective Surface and Grid Array* (John Wiley & Sons, Inc., New York, 1995)
[5] R. Mittra, C. H. Chan, and T. Cwik, Proc. IEEE **76**, 1593 (1988)
[6] J. Schultz, D. V. Ivanov, and K. R. Farmer, Proc. of the 14th Biennial University/Government/Industry Microelectronics Symposium 153 (2001)
[7] Q. Zhang, V. Bharti, and X. Zhao, Science **280**, 2101 (1998)
[8] Q. M. Zhang, H. Li, M. Poh, F. Xia, Z.-Y. Cheng, H. Xu, and C. Huang, Nature **419**, 284 (2002)