Fabrication of frequency-selective surfaces using microlens projection photolithography

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This letter describes the use of microlens projection photolithography (μLPL) for the fabrication of repetitive metallic micropatterns, and the application of these patterns as frequency-selective surfaces. Microlens projection photolithography uses an array of microlenses (diameter $d = 1-1000$ micrometers) to project an array of images of an illuminated mask into photoresist. We converted these arrays into patterns in metals by electron beam evaporation and lift off. This technique can produce arrays over areas $>10\ \mathrm{cm}^2$ with submicrometer feature sizes in a single exposure. We fabricated arrays of metallic micropatterns on substrates transparent to infrared radiation, and demonstrated that appropriate patterns acted as frequency-selective filters. [DOI: 10.1063/1.1477941]

Arrays of metallic patches act as arrays of conducting dipoles on illumination with electromagnetic radiation.[1] The arrays of dipoles act as spectrally resonant components, and function as spectral filters.[1–6] For these elements to work in the midinfrared, the length of the conducting dipoles should have dimensions from 1.0 to 4.0 μm; precise control of linewidths is required for accurate control of spectral bandwidths.[7,8] Conventional microlithographic—electron-beam, ion-beam, and x-ray lithography—can generate these metallic structures with linewidths less than 500 nm.[7–11] Although these technologies produce high-quality structures, they require specialized facilities. For electron-beam and ion-beam lithography, fabrication is time consuming.

Unconventional lithographic techniques such as contact-mode phase-shift lithography and undercut etching have been applied for the fabrication of frequency-selective surfaces (FSS) with nanoscale feature sizes.[12,13] These techniques are well suited for the fabrication of sub-200 nm linewidths, and they produce uniform patterns over areas of several cm^2. Although they are very useful for the generation of FSS consisting of repetitive nanoscale frames, these techniques can only produce patterns with constant linewidth. These techniques are limited to the fabrication of frame-type micropatterns, and they can not easily generate linewidths >300 nm.

Here, we demonstrate an alternative method for the fabrication of FSS using microlens projection lithography (μLPL);[14,15] This technique is a form of photolithography in which a microlens array acts as an array of reduction lenses and projects the image of an illuminated mask pattern as an array of micropatterns. We have demonstrated the use of μLPL for generating arrays of micropatterns.[14,15] We record the array of images produced by the lenses in a layer of photoresist by placing the resist layer on the image plane of the lens array for exposure. This technique can generate arrays of patterns with features smaller than 300 nm using broadband illumination with a wavelength ranging from 350–450 nm, and can provide a reduction of pattern size over 10^3 in a single step. This technique eliminates the use of a stepper in certain circumstances, and has the potential to be particularly useful for large-scale production of repetitive patterns where multilayer registration is not required.

Although it is possible to use an array of large microlenses ($>30\ \mu$m) to produce an array of patterns each of which has smaller ($<10\ \mu$m) subpatterns, the patterns produced in the off-axis image field, and in the regions between neighboring lenses, can be distorted. Therefore, it is generally better that each microlens produces only one micropattern on its central image field. In this letter, we use arrays of smaller lenses ($<30\ \mu$m) to generate arrays of simple micropatterns[14] ($<10\ \mu$m) for the fabrication of midinfrared FSS.

We have used μLPL to fabricate FSS consisting of arrays of microscale crosses or tripoles with length of each arm $\sim 2-4\ \mu$m. The linewidth of each element is $\sim 0.5-1\ \mu$m. We have produced FSS with uniform micropatterns over areas $>4\ \mathrm{cm}^2$. The frequency selective filters were fabricated on substrates of crystalline ZnSe (refractive index ~ 2.4 at $\lambda = 11\ \mu$m), which is transparent to wavelength from 0.6 to 16 μm. Optical measurement shows that these patterns act as notch filters in the infrared range.

In previous articles,[14,15] we have demonstrated the use of two types of microlenses for microlens projection lithography: (i) self-assembled monolayers of transparent microspheres, and (ii) two-dimensional arrays of plano-convex microlenses fabricated using reflow of melted photoresist. The details of their preparation are available in the references.[14,15]

We fabricated thin films of poly(dimethysiloxane) (PDMS), (Sylgard 184, Dow Corning, Midland, MI) on the surface of lens arrays as spacer elements that separate the lenses from the photoresist at a uniform distance equal to the image distance. The distance $\boldsymbol{d}_{\mathrm{mask}}$ of the transparency mask from the lens array is much larger than the focal length of the lenses ($\boldsymbol{d}_{\mathrm{mask}} > 100 \times \boldsymbol{f}_{\mathrm{lens}}$). Thus, the image distance is about the same as the focal length, and the PDMS films were fab-

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ricated to have thicknesses equal to the focal length of the lens arrays.

PDMS is an elastomer that is widely used in soft lithography.[16,17] It is transparent down to 280 nm, and provides conformal contact with photoresist that minimizes the formation of air gaps between photoresist and lenses. These properties make it an ideal spacer element for μLPL; it generates uniform spacing between the lens array and the photoresist without the use of equipment for vertical alignment.

This technique requires only a minimal optical system.[14] An optical projector (an overhead transparency projector) or a UV lamp is used as a light source for exposure. The pattern to be used was printed onto a transparency using a desk-top printer (3386 dpi). We placed the transparency mask on top of the light source. The microlens array was positioned about 15–50 cm above the mask, depending on the numerical aperture of the lens array. To perform photolithography, we exposed the resist layer (photoresist: Microposit 1805, Shipley Inc.) to the light source through the microlens array. For a resist layer with a thickness $\sim$0.5 μm, the exposure takes about 0.5–4 min, depending on the pattern on the mask, the numerical aperture of the lens array, and the light source.

After exposure, the membrane containing the microlens array was removed from the resist, and the resist was developed in a solution of sodium hydroxide (Microposit 351 Developer). We dried the resist layer under a nitrogen stream; the developed layer consisted of an array of micropatterns. To transfer the micropatterns in the resist layer into a thin film of metal, we coated the substrate with a thin film of aluminum by electron beam evaporation and lifted off the photoresist in acetone.

To give useful efficiency for the FSS, dense arrays of microlenses are required to fabricate dense arrays of metallic micropatterns. Since two-dimensional (2D) arrays of transparent microspheres act as dense arrays of microlenses, we used them to generate hexagonal arrays of metallic micropatterns. The cost of microspheres is significantly lower than that of chromium masks with dense, sub-10 μm patterns.

Figure 1 shows two patterns of 50 nm aluminum thin films on ZnSe substrates, generated using a 2D crystal of 6 μm polystyrene (PS) microspheres. The pattern of the mask that produced the corresponding micropattern is placed at the corner of the photomicrograph. The first pattern consists of arrays of cross-shaped structures in thin-film aluminum; the length of each arm of the cross was $\sim$3.5 μm. This pattern acts as a FSS. The second pattern consists of arrays of tripole-shaped structures in thin-film aluminum with the length of each arm $\sim$2.3 μm. Both patterns are capacitive resonant meshes that exhibit bandstop transmittance properties.

The sizes of the cross-shaped or tripole-shaped micropatterns are about half of the diameter of the 6 μm microspheres. We fabricated the micropatterns at this scale in order to position the resonant frequencies between 10 and 15 μm.

We used a Fourier transform infrared spectrometer (Nexus 670, Nicolet) to measure the spectral transmittance of the samples. Figure 2(a) shows the transmission spectrum of the cross-type FSS shown in Fig. 1(a). The resonant frequency occurs at a wavelength around 12.6 μm, and has a transmittance of $\sim$57% of the light at this wavelength. The

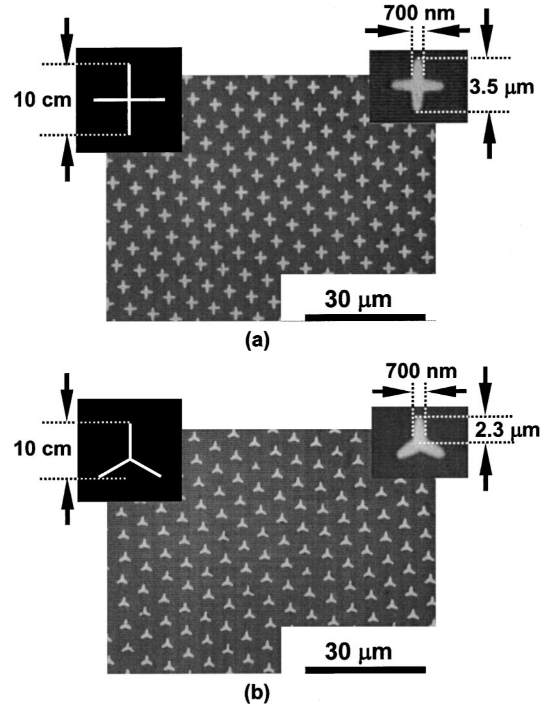

FIG. 1. Microphotographs of two types of FSS. (a) Tetrapolar FSS. (b) Tripolar FSS. The feature sizes in both types of FSS are about 700 nm. Both FSS were produced using 6 μm PS spheres.

spectrum shown in Fig. 2(b) corresponds to the tripole-type FSS shown in Fig. 1(b). The resonant frequency is around 12.3 μm, and the transmittance is about 63% of the light at this wavelength. The resonant frequencies of the cross-type and tripole-type FSS can be expressed by Eqs. (1)–(3).

$$\lambda_r \sim n_{\mathrm{eff}} 4 \times l_{\mathrm{cross}},$$

$$l_{\mathrm{cross}} = \text{length of each arm of a cross; for cross-type FSS,} \quad (1)$$

$$\lambda_r \sim n_{\mathrm{eff}} 3 \times l_{\mathrm{tripole}},$$

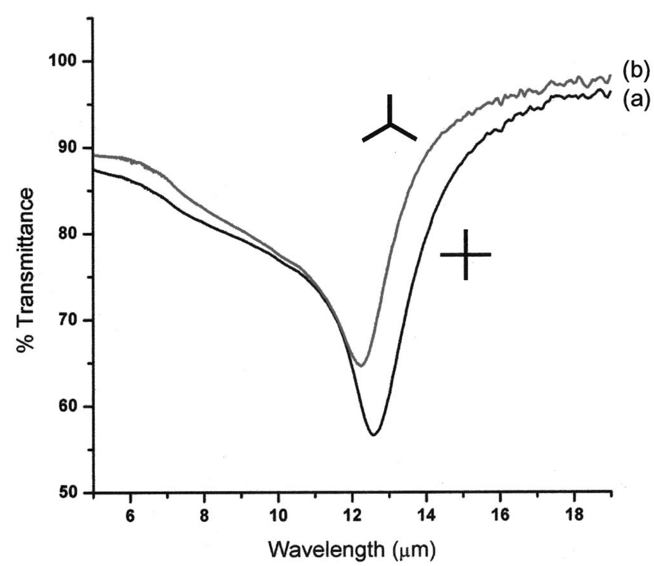

FIG. 2. Spectral transmittance of the FSS. (a) Transmission spectrum of the cross-type FSS shown in Fig. 1(a). (b) Transmission spectrum of the tripole-type FSS shown in Fig. 1(b).

$$l_{\text{tripole}} = \text{length of each arm of a tripole}, \tag{2}$$

$$n_{\text{eff}} = \sqrt{(n_1^2 + n_2^2)/2}. \tag{3}$$

Here, n_1 and n_2 are the refractive indices of the medium above (air, $n_1 = 1$) and below (ZnSe substrate, $n_2 = 2.4$) the metallic patterns.

Figure 1 shows the length of the cross is about 3.5 μm and the arm of the tripole is about 2.3 μm. Based on the formulas, the theoretical values of the resonant frequencies of these two FSS are about 12.8 μm and 12.7 μm, respectively. The measured results are consistent with the theoretical values.

The PS microspheres used for this technique have a size variation of $\sim 10\%$. The monolayer of microspheres is polycrystalline, and has defects and grain boundaries. These factors result in broadening of the full width at half maximum of the resonant spectra and the asymmetry of the spectral curve at the resonant wavelength.

Arrays of lenses with diameters of 1–1000 μm can be used in μLPL to produce repetitive patterns with feature sizes in the range from micrometers to submillimeters. The micropatterns are uniform over areas > 10 cm^2. The uniformity of the micropatterns depends on several factors: (i) the quality and uniformity of the microlenses, and (ii) the uniformity of the thickness of the PDMS spacer. The fabrication of uniform micropatterns over large areas requires the use of uniform microlenses and spacers.

This technique has several characteristics useful for the fabrication of FSS: (i) Compared with conventional photolithography, it does not require chrome masks; It uses transparency masks with mm-scale feature sizes. Since the patterns on transparency masks can be easily and quickly generated using a desk-top printer, this technique provides a cost-effective route for both the fabrication and rapid prototyping of frequency-selective filters in the midinfrared range of frequencies; (ii) One lens array with different patterns on transparency masks can produce a variety of repetitive micropatterns that act as FSS with different levels of spectral performance. Chrome masks used in conventional lithography can produce only one pattern. (iii) Conventional lithography requires the use of expensive vertical alignment equipment to achieve uniform spacing between the chrome mask and the photoresist; μLPL uses a single, inexpensive elastomeric spacer to generate a uniform image distance between the lens array and the photoresist. (iv) Since μm-size patterns formed in the resist layer correspond to the cm-size pattern on the mask, a sub-mm scale change in the pattern on the mask would result in the sub-100 nm scale change in the micropatterns. Thus, we can tune the shape of the micropatterns at the sub-100 nm scale by a sub-mm scale change in the mask. This technique offers the unique advantage of very fine tuning the micropatterns without using expensive, high-precision equipment.

Microlens projection lithography is well suited for the fabrication of large-area, single-layer, FSS. We have demonstrated two types of single-layer FSS in this letter. Other types of single-layer FSS can be fabricated using this technique with appropriate patterns on transparency masks.[3,9] Multiple μLPL with multiple masks can be used to fabricate multiple layers of patterned, metallic thin films that act as multilayer FSS.

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