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A two dimensional array of optical interference filters produced by lithographic alterations of the index of refraction

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ABSTRACT

We describe a new concept for producing, on a single substrate, a two-dimensional array of optical interference filters where the pass-band of each element can be independently specified. The interference filter is formed by optically contacting two dielectric mirrors so that the top quarter-wave films of the two mirrors form a Fabry-Perot cavity having a half-wave thickness. In the new device, we propose to etch an array of sub-wavelength patterns into the top surface of one of the mirrors before forming the cavity. The patterns must have a pitch shorter than the operational wavelength in order to eliminate diffraction. By changing the index of refraction of the half-wave layer, or the optical thickness of the cavity, the patterning is used to shift the pass-band and form an array of interference filters. One approach to producing the array is to change the fill factor of the pattern. Once the filter array is produced it may be mated to a two-dimensional detector array to form a miniature spectrophotometer.

KEYWORDS: sub-wavelength structures, interference filter, spectrophotometer,

2. CURRENT TECHNOLOGY FOR FILTER ARRAYS

Optical interference filters appear in a number of forms. The class of filters with the highest transmission and narrowest linewidths are Fabry-Perot filters. These filters are formed by sandwiching a half-wave (or some multiple thereof) spacer layer between two mirrors. The lowest absorptive losses are found in mirrors made from multilayer dielectric stacks that are usually quarter-wave in thickness. The pass-band of these filters (i.e. the center wavelength, λ_0) is determined by the optical thickness of the spacer layer. The bandwidth is determined by both the optical thickness of the spacer layer and the reflectivities of the two mirrors. The most common Fabry-Perot filters commercially available have pass-bands that are spatially uniform with variations as small as 0.1%. Filters with spatially varying pass-bands are also commercially available and are manufactured by proportionally varying the thickness of all the layers uniformly across the surface of the filters. These filters, called wedge filters, are either circular (circular variable filter - CVF) or linear (linear variable filter - LVF). In the former, the thicknesses of the multilayer films vary linearly with the angular position on a circular substrate; in the latter, they vary linearly with position across a rectangular substrate.

Although wedge filters are widely used, they have several limitations. First, it is not possible to have both large dispersion (>> 10 nm/mm) and retain other desirable characteristics. The dispersion is proportional to the wedge angle; however, a large wedge angle results in poor transmission characteristics (due to non-normal reflections from the angled mirror facet), and an increase in spectral bandwidth (due to wavefront inhomogenity across the angled facets). Owing to these limitations, wedge filters are large (e.g. typical LVFs in the 300 nm - 700 nm spectral range are 60 mm in length) and have dispersion of about 5-10 nm/mm. CVFs are typically 25-50 mm in diameter and have a dispersion of 1 nm/degree. Significant improvements in these numbers are not expected; therefore, ultra-miniaturization of devices employing LVFs or CVFs is not possible with existing technology.

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Another restrictive feature of wedge filters is that the pass-band can change only in a continuous manner across the substrate. In designing an optical sensors one may be interested only in a relatively small number of distinct, and non-uniformly spaced spectral bands. However, with a wedge filter one cannot pick and choose the desired channel unless one has a well collimated and uniform beam that encompasses all the desired channels. Since maintaining a good collimation along with acceptable light levels is difficult (especially if the channels are separated by 60 mm), it is necessary to either move the filter (e.g. a rotating CVF), or steer the beam. Neither of these strategies is well suited for extremely rapid data collection, especially if the desired channels are widely spaced throughout the spectrum.

Another impediment to the miniaturization of a spectrophotometer based on a wedge filter is that the filter is essentially a one-dimensional structure. Typically, pass-bands can be varied along only one dimension (linear position in LVF and azimuthal angle in CVF). A two-dimensional wedge filter is difficult to fabricate and to our knowledge, none is available commercially.

3. A NEW TECHNOLOGY

We describe here a new technique to produce on a single substrate, a two dimensional array of optical interference filters in which the pass-band at any spatial location on the substrate is a variable, user supplied parameter. A schematic diagram of the new type of filter array is shown in Fig. 1. This array is arranged in a pixel format similar to that of a two-dimensional photodetector array (e.g. silicon CCD array). This is to suggest that such a filter array, in conjunction with a two-dimensional detector array, can form a compact spectrophotometer. However, unlike conventional miniature spectrophotometers that utilize LVFs and CVFs, each channel can be individually assigned a different pass-band over a relatively large spectral range ($\Delta\lambda/\lambda_0 \sim 0.1$ to 0.35). In sensor applications, where information at only a few wavelengths is required, a spectrophotometer based on this type of filter array can be extremely miniature since the pixel size can be made as small as the dimensions of the detector pixel (< 100 μm).

Our technique is to form an interference filter by optically contacting two dielectric mirrors, where a series of one and two dimensional periodic steps is lithographically patterned on the top surface of one of the dielectric mirrors. A sketch of our design is shown in Fig. 2. Each dielectric mirror (with three pairs of alternating layers of high index Si and low index SiO_2) has a reflectivity of approximately 98%. Note that both of the multilayer mirrors terminate with a low index layer. Since each of the layers is a quarter-wave thick, combining the two mirrors yields a cavity width, $\lambda_0/(2n_L)$, where n_L is the index of refractive of the low index material. The two mirrors on the top and bottom of this cavity form a prototypical optical interference filter that is well documented in the literature, with the pass-band centered at λ_0 and a bandwidth determined by the finesse.

The pass-band is changed by etching a periodic pattern onto the top surface of one of the mirrors. The patterned surface appears as a set of periodic grooves or steps in the outer quarter-wave layer of one of the dielectric mirrors. In this quarter-wave layer, the index of refraction is different from that of the bulk film and this difference can be controlled by varying the geometry of the pattern (e.g. changing the pitch and width of the grooves). Varying the index of refraction of the cavity region changes its optical thickness thereby changing the pass-band of the interference filter. For the one-dimensional pattern in Fig. 2, the effective index of refraction is approximated as:

$$n_\parallel^2 = n_{Air}^2 f + n_{Layer}^2 (\Lambda - f) \tag{1}$$

for polarization parallel to the groove direction, and

$$\frac{1}{n_\perp^2} = \frac{1}{n_{Air}^2} f + \frac{1}{n_{Layer}^2} (\Lambda - f) \tag{2}$$

for polarization perpendicular to the groove direction, where Λ is the pitch of the grooves and f is the dimension of the etched region (the fill factor, f, is defined as f/Λ, also, $0 \leq f \leq 1$, where f=0 indicates no etched region). These expressions assume that there are no diffracted orders other than the zeroth order (hence, such structures are often called zeroth order gratings). Eqs. (1) and (2) have been shown experimentally to be reasonably accurate for $\Lambda \leq \lambda/2$ [1]. In Fig. 3, we plot the transmission curve as a function of the fill factor for a groove pitch of 400 nm. This figure is obtained from a multilayer thin films computer code, assuming patterning on only one of the mirror surfaces. The layer thicknesses of the quarter wave layers are chosen to have the pass-band for f=0 centered at 1550 nm. From Fig. 3, it is seen that by changing the fill factor, the pass-band of the filter changes. The spectral range of the tuning can be readily shown to depend on the index of refraction of the cavity dielectric:

$$\frac{\Delta\lambda}{\lambda_0} = \frac{1}{4}\frac{(n-1)}{n} \quad . \tag{3}$$

The range, $\Delta\lambda$, is 274 nm for Si, and 120 nm for SiO_2, when λ_0 is 1550 nm. This equation assumes that only half of the cavity is patterned. Twice the range is possible if one is willing to pattern the surface of both mirrors before forming the cavity.

From Eqs. (1) and (2), it is seen that the etched layer has an index of refraction that is different for differing polarizations. This birefringence can be quite large and has been measured experimentally (for a single layer of patterned SiO_2) to be as much as $\Delta n = n_{\perp} - n_{\parallel} = 0.06$ [1]. Therefore, the use of a grooved spacer layer such as that shown in Fig. 2, yields a narrow band polarization filter with polarization extinction ratios better than 10^3, as is seen in Fig. 4. By introducing two-dimensional patterns, but maintaining the sub-wavelength periodicity in all symmetry directions, such as that shown in Fig. 5, the birefringence of the filter can be eliminated. This is particularly important for optical sensor work where polarization independent behavior is normally desired.

Structures with groove periods smaller than the wavelength such as that shown in Fig. 2 have been investigated for anti-reflection coatings[2-5]. However, such work has not been extended, to our knowledge, to the area of interference filters, as suggested herein.

4. CONCLUSIONS AND COMMERCIALIZATION POTENTIAL

This new type of interference filter array overcomes the principal limitations of the wedge filter that were discussed in Section 2. In summary, the new technology has the following features: (1) individual array elements are spectrally flat, (2) pass-bands can be specified independently for each array element, (3) two dimensional arrays can be readily fabricated, and (4) miniaturization is readily achieved.

There are at least two uses for these devices. (1) *Integrated Optical Sensors.* The optical filter when used in conjunction with a broadband semiconductor diode source and an array detector is a miniature spectrophotometer. Such a spectrophotometer can form the basis of a low-cost miniature optical sensor. (2) *Polarizing Interference Filters.* As described earlier, by appropriate patterning, the optical interference filter can be made polarization sensitive with extinction ratios better than 10^3.

An attractive feature of our design from the viewpoint of its commercialization is its potentially low manufacturing cost. It is expected that over 200, 5x5 element arrays (with an element size of 150 µm x 150 µm) can be fabricated on a single 2 inch substrate. For a typical 2 inch substrate, costing \$200, the coating cost is about \$1000 and the e-beam lithography cost is about \$2000. Assuming that 200 arrays can be made on each substrate, the manufacturing cost per filter array, excluding dicing and mounting, is only \$16. This cost can be further reduced if multiple substrates are coated per coating run (usually 10-15 two inch substrates can be coated on each run). This cost is to be compared with currently available filters such as LVF and CVF where natural economies of scale are more limited and the retail cost is typically $300-$500.

5. ACKNOWLEDGMENTS

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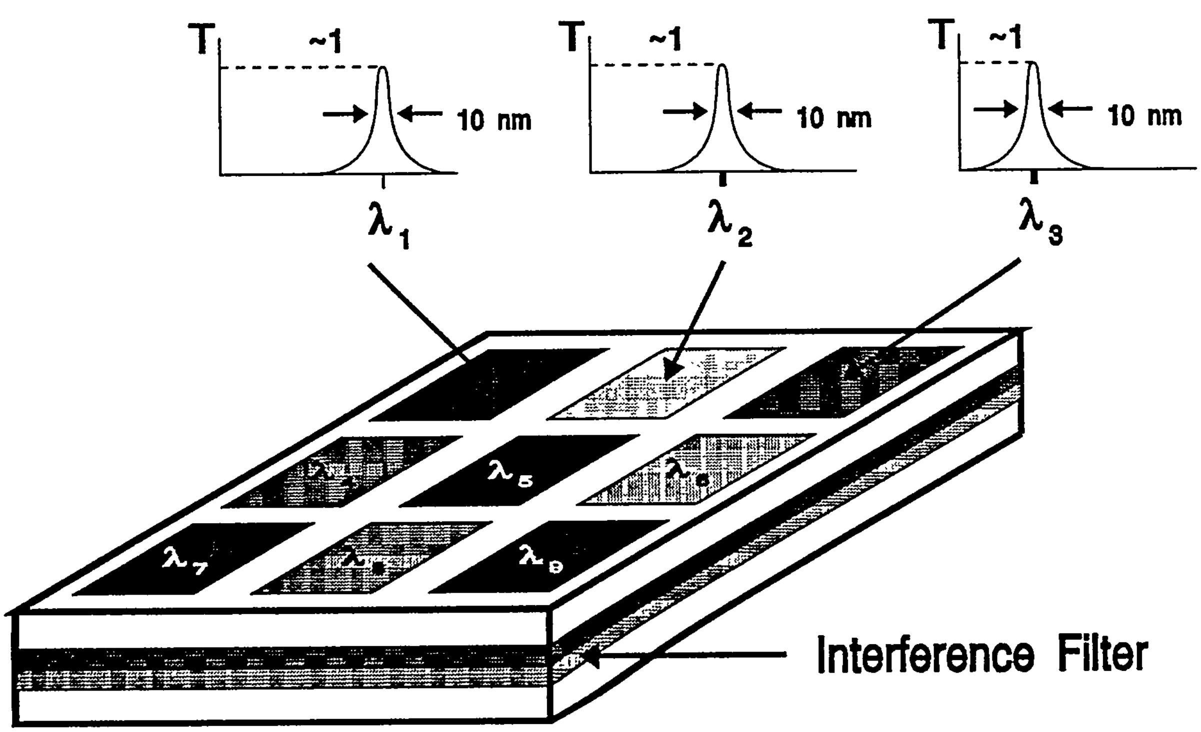

Figure 1. Schematic diagram of a two-dimensional filter array.

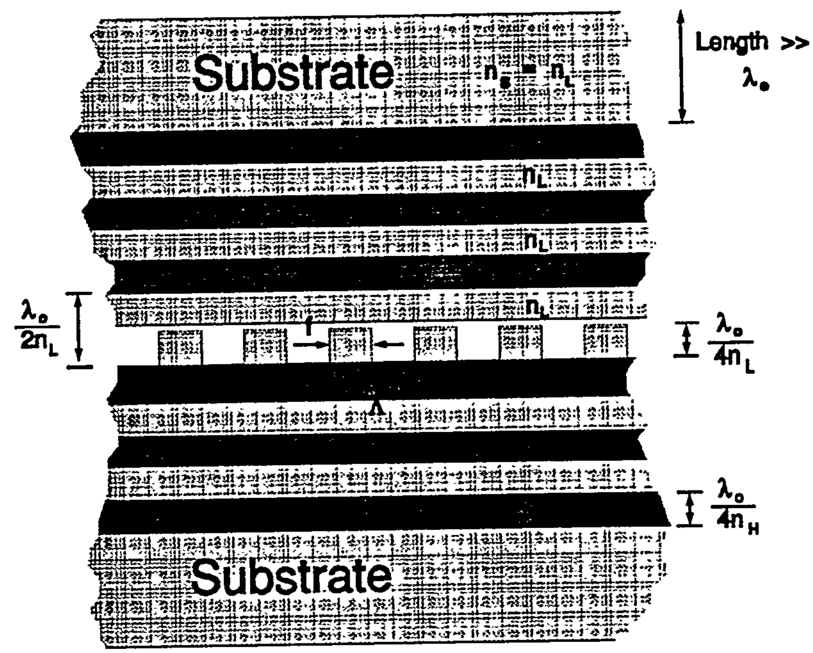

Figure 2. Cross-section of a Fabry-Perot filter that is tuned by sub-wavelength patterning. The high and low index materials, n_H and n_L, are assumed to be Si and SiO_2 for the calculations of Figs. 3 and 4.

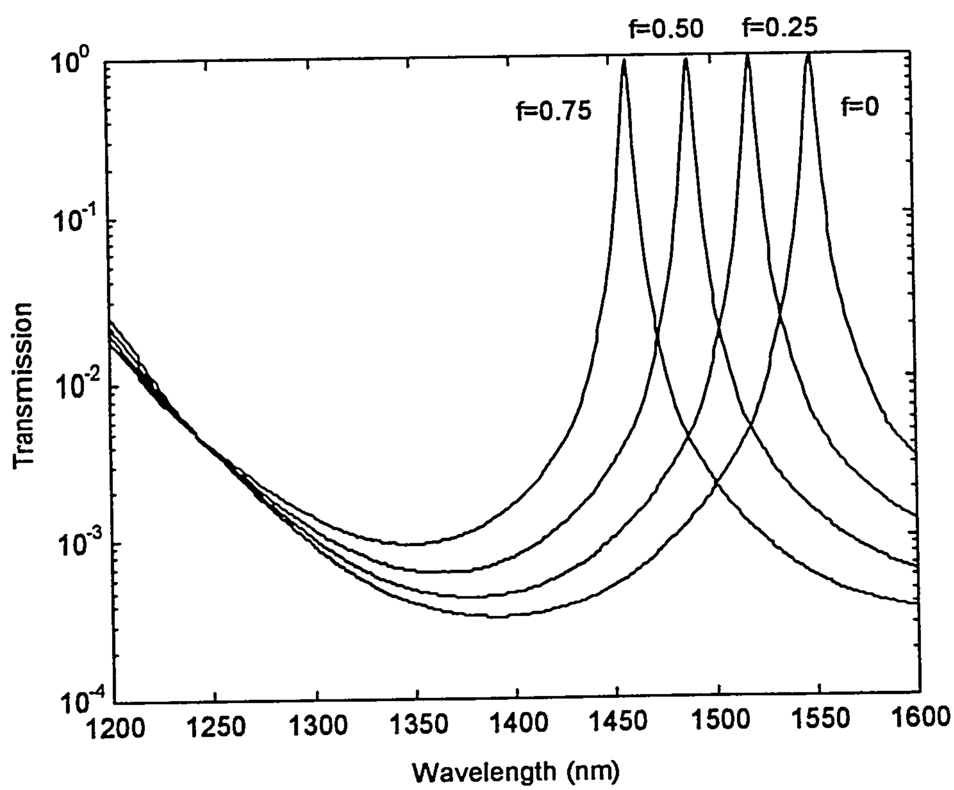

Figure 3. Calculated transmission vs. wavelength curves for the device in Fig. 2. Several values of the fill factor, f, from 0 to 0.75, are plotted. Shifts are double what is shown if patterning is on both mirror surfaces.

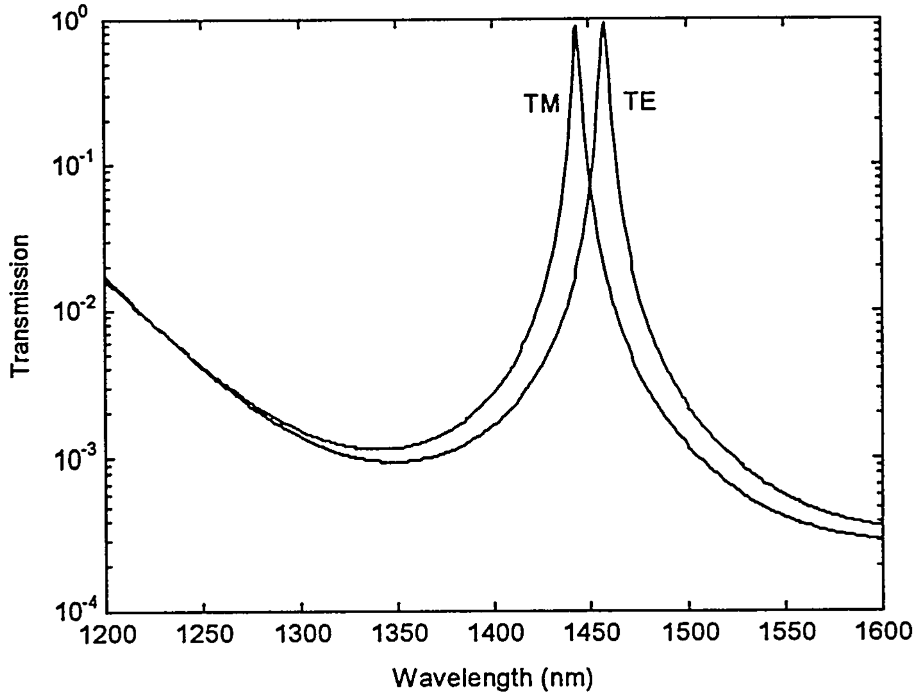

Figure 4. Calculated transmission vs. wavelength curves for TE (parallel to grooves), and TM (perpendicular to grooves) polarization for the device in Fig. 2. The value of the fill factor is 0.75.

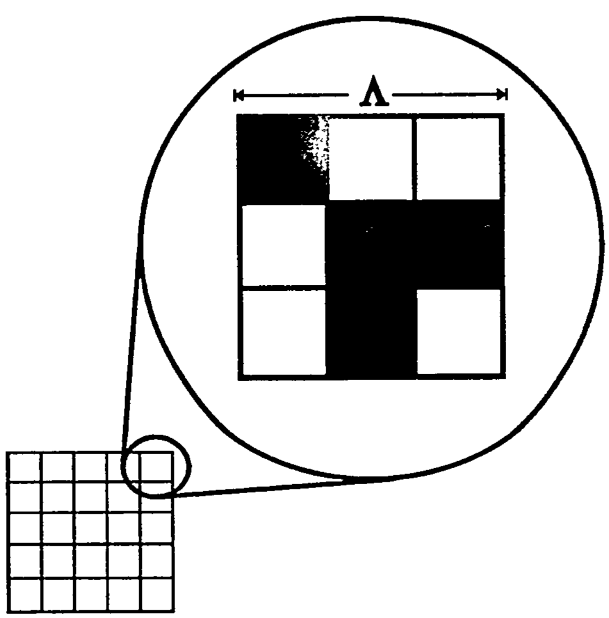

Figure 5. Example of a two-dimensional pattern where the fill factor is varied by turning on or off the sub-pixels. The pitch, Λ, of the repeating pattern is chosen to be less than half the wavelength to avoid diffraction.