1. Introduction

Optical resonant filters can be an alternative for Bragg gratings filters\textsuperscript{1,2} that are used for notch filtering in modern optical communications. Bragg gratings can be realized reliably and with acceptable accuracy in positioning the center wavelength of the notch-filtering window. Moreover, they can be modified to compensate for group velocity dispersion and to reduce the sideband effects by use of apodized index profile gratings. In this paper we investigate the potential for the use of optical resonant filters in optical communication systems by fabricating an optical resonant filter with a close-to-rectangle filtering profile. The absence of the sidebands that exist in the Bragg filtering profile makes the optical resonant filters an attractive alternative. Additionally, realizing a close-to-rectangle filtering profile is significantly useful in establishing more efficient dense wavelength division multiplexing communications for two reasons. First, the sharpness of the filtering window that is assigned to a particular channel largely determines the trade-off strategy between the bandwidth efficiency and the quality of transmission. If the filtering window has a perfect rectangle shape, a perfect channel (i.e., without dispersions, cross talk, or noise) could yield close to 100\% bandwidth efficiency, provided that all of the filtering windows were placed adjacent to one another to remove the channel cross talk that occurs when the filtering windows overlap. Thus reducing the limitations on the bandwidth efficiency at the transmitting and receiving sides by use of quality filters eventually enhances the bandwidth efficiency. Second, rectangular filters allow all the spectral components within the filtering window to undergo uniform modulation. For long transmission paths in which the signal is amplified several times, the problem of nonuniformity within the passband becomes significant because some spectral components are highly magnified and saturate the optical amplifiers, whereas other spectral components decay along the communication path.

2. Theory and Experiment

Before proposing methods for realizing optical resonant filters with a close-to-rectangle filtering profile, a brief review of the optical resonant filters theory is presented.

Optical resonant filters’ principle of operation is the anomalous reflection, discovered by Wood in 1902.\textsuperscript{3} Considerable theoretical and experimental work has been done since then.\textsuperscript{4–10} It was found that two major components are needed to observe the anomaly: waveguiding and coupling effects. Waveguiding can be realized by two means: (1) a surface plasmon excitation, such as on the surface of metals when they are shined with a suitable laser beam or (2) a dielectric layer that is sandwiched between two media with refractive indexes lower than that of the waveguide. Coupling is realized by use of a diffraction grating that is integrated with the
waveguide. All of our work was based on the second type of waveguiding.

The optical resonant filter structure is configured as shown in Fig. 1, and the excitation condition, which is also the main equation that describes the spatial-spectral filtering, is given by:

\[
(n^s - m \frac{\lambda}{\Lambda})^2 + \sin^2 \theta = \left(\frac{\lambda \kappa}{4 \pi}\right)^2,
\]

where \(\kappa\) is the Bragg coupling coefficient; \(L\) is the period of the light-traveling sequence inside the waveguide; \(\sigma\) is the grating depth; \(\lambda\) is the wavelength; \(\Lambda\) is the grating period; \(\theta\) is the angle of incidence; \(m\) is the diffraction order; and \(n^s\) is the effective refractive index, which is related to the indices \(n_1, n_2,\) and \(n_3\) of the superstrate, the waveguide layer, and the substrate, respectively, and to the waveguide thickness \(d\) by:

\[
\tan(\sigma d) = \frac{(p + q)h}{h^2 - pq},
\]

and for electric polarization light:

\[
q = k(n^{s2} - n_1^2)^{1/2},
\]

\[
p = k(n^{s2} - n_3^2)^{1/2},
\]

\[
h = k(n_2^2 - n^{s2})^{1/2},
\]

\[
k = \frac{2\pi}{\lambda}.
\]

Equation (1) indicates a hyperbolic relation between the spectral and the spatial filtering. The spectral gap between the lower and upper parts of the hyperbolic curve is a function of the Bragg coupling factor \(\kappa\) and the wavelength \(\lambda\). If \(\kappa\) is relatively high, which is realized in the presence of deep gratings, we find a clear splitting of the two sections of the hyperbolic curve. It is evident that at normal incidence there are two wavelengths that satisfy Eq. (1), whereas shallow gratings with relatively low \(\kappa\) produce one sharp resonance. This becomes obvious when \(\kappa\) is set to zero and the excitation condition in Eq. (1) reduces to a linear relation between the spatial \((\theta)\) and the spectral \((\lambda)\) parameters, a condition that is satisfied at normal incidence by a single wavelength:

\[
n^s = m \frac{\lambda}{\Lambda} \pm \sin \theta.
\]

In the first approach a close-to-rectangle-shape resonant filter is realized by adjusting \(\kappa\) in a compromising manner such that the two peaks shown in the strong Bragg coupling case overlap and produce a wider, flattened filtering window. In other words, it is possible to produce a close-to-rectangle filtering profile by use of resonance sharpness and resonance-peak overlapping.

The flatness, the flatness width, the full width at half-maximum (FWHM), and the maximum reflection \((R_{\text{max}})\) are features that determine the bandwidth efficiency and the uniformity of the filtering window. The grating depth and the waveguide optical constants allow the filter designer the flexibility to meet the filter requirements for optimal device performance.

A comprehensive design problem can be formulated once the effects of the filter features on transmission quality (i.e., the bit error rate) and bandwidth efficiency are measured and once the relations between the filter’s physical values and its features are established. A merit function that expresses the bit error rate and the bandwidth efficiency must be minimized with respect to the physical values of the filter. Relations between the filter’s physical values (waveguide optical constants, waveguide thickness, grating period, and grating depth) and its features can provide a tool for the filter designer and are worth presenting here. To do this we use relations that describe the \(R_{\text{max}}\) and the FWHM of an optical resonant filter with weak Bragg coupling:

\[
R_{\text{max}} = \left(\frac{r_{\alpha_p} - 2\alpha_s}{\alpha_p + 2\alpha_s}\right)^2,
\]

\[
\text{FWHM}_s = \frac{(\alpha_p + \alpha_s)\lambda}{\pi},
\]

where \(\alpha_p\) is the waveguide absorption and scattering losses; \(\alpha_s\) is the out-coupling losses, which increase with grating depth; and \(r_t\) is the Fresnel reflection.
from the waveguide–superstrate interface. The modified filter features can be expressed as

\[
R_{\text{max}} = \frac{\alpha_{pk} - 2\alpha_{rk}}{\alpha_{pk} + 2\alpha_{rk}},
\]

\[
\text{FWHM} = \frac{\tau \Lambda}{2} + \frac{2\lambda (\alpha_{pk} + \alpha_{rk})}{\pi},
\]

\[
W = \frac{\kappa \lambda \Lambda}{4\pi},
\]

\[
F = \frac{\text{FWHM}}{W} = \frac{4(\alpha_{pk} + \alpha_{rk})}{\kappa \lambda},
\]

where \(W\) is the flatness width, defined as the spectral difference between the two resonance wavelengths; \(F\) is the flatness, expressed as the ratio between the FWHM for the single resonance wavelength case (FWHM\(_s\)) to the flatness width; \(\alpha_{pk}\) is the waveguide absorption and scattering losses for an optical resonant filter with strong Bragg coupling; and \(\alpha_{rk}\) is the out-coupling losses for an optical resonant filter with strong Bragg coupling.

For the strong Bragg-coupling case, a mutual coupling between the forward and the backward energy propagations takes place, resulting in a different distribution of energy within the excited waveguide. For example, a photon that is propagating within the excited waveguide in the forward direction has a chance to change its direction backward and then forward again because of the mutual coupling between the two propagating directions. This produces a different sense of the optical losses. A relation between \(\alpha_{pk}\), \(\alpha_{rk}\) and \(\alpha_{f}\), \(\alpha_{r}\) can be established by reference to a couple of differential equations that describe the forward and backward coupling produced by a Bragg grating in a gain medium, such as the distributed feedback laser case,\(^{11}\) but with losses consideration instead of amplification at resonance:

\[
\frac{dA}{dz} = \kappa B + \alpha A,
\]

\[
\frac{dB}{dz} = \kappa^* A - \alpha B,
\]

where \(A\) is the forward propagating field intensity, \(B\) is the backward propagating field intensity, \(\alpha\) can be either \(\alpha_f\) or \(\alpha_r\).

Equation (7) can be reduced to

\[
\frac{d^2A}{dz^2} = (\kappa^2 + \alpha^2)A.
\]

Also recalling that the general optical losses \(\alpha_k\) are expressed by

\[
\frac{dA}{dz} = -\alpha_k A,
\]

where \(\alpha_k\) can be either \(\alpha_{pk}\) or \(\alpha_{rk}\).

Deriving Eq. (9) with respect to \(z\) yields

\[
\frac{d^2A}{dz^2} = -\alpha_k \frac{dA}{dz}.
\]

Substituting Eq. (9) into Eq. (10) yields

\[
\frac{d^2A}{dz^2} = \alpha_k^2 A.
\]

Comparing Eqs. (8) and (11) yields

\[
\alpha_k = (\alpha_f^2 + \kappa^2)^{1/2}.
\]

The model given in Eqs. (6)–(12) can, to a certain degree, help the filter designer set the device’s physical values.

3. Experiments and Results

As discussed above two technological components are needed for the optical resonant filter fabrication: a waveguide film and a gratings coupler. The waveguide film was deposited on a standard BK-7 glass substrate with a refractive index (1.51 at \(\lambda = 632.8\) nm) less than that of the deposited film. The holographic grating (\(\Lambda \approx 500\) nm) was then introduced on top of the waveguide layer. We used rf magnetron sputtering to deposit a mixture of silica and titania for the waveguide fabrication.\(^{12,13}\) Changing the forward sputtering power of the two magnetrons controls the silica–titania mole ratios and thus the optical constants of the waveguide. It was noticed that when the silica mole ratio increases, the real and imaginary refractive indices decreases in the deposited film, whereas titania has the opposite effect. This provided the flexibility to compromise between the waveguide energy confinement and the propagation length.

A reliable real-time optical monitoring system that is based on recording the reflection fringes from the growing film on a silicon substrate was developed to control the film optical constants.\(^{14,15}\) Figure 2(a) shows the configuration of the setup, and Fig. 2(b) shows the recorded reflection fringes (dashed curve) and the best fit (solid curve) when depositing a silica–titania mixture on a silicon substrate. The fitting was performed by use of the mean squared errors, and the fitting parameters were the real refractive index and the deposition rate. Figure 2(c) shows the region in the real-refractive-index and the deposition-rate space where the error of fitting is less than the doubled minimum error of fitting. The area of this region, along with the minimum error of fitting, provides a measure of the reliability of the fitting. The small mismatch between the data and the fit is attributed to ignoring the film optical losses and the surface roughness during the fitting. Nevertheless, the envelope of the data fringes graph [dashed curve in Fig. 2(b)] can be used to extract the film optical losses and the root mean square of the film surface roughness,\(^{16}\) which were found to be 0.5 dB/mm and 0.42 nm, respectively.

To fabricate the grating a coherent deep-ultraviolet
beam, from the second-harmonic generation of an Ar\textsuperscript{+} laser with a 257-nm wavelength, was spatially filtered, collimated, and then spatially split into two beams, one delayed from the other within the coherence length of the laser beam. The grating period was controlled by the angle of the two coherent interfering beams on the photoresist film, which was governed by a computer-controlled rotation stage with 10\textsuperscript{−3} deg resolution. The sinusoidal interference pattern was printed on SPR505-A (ethyl lactate, n-butyl acetate, and xylene) photoresist film with thickness \(\approx 450\) nm. Figure 3 shows the photoresist exposure setup that was used for the grating patterning. The exposed photoresist film was developed to obtain the grating formation and then hard backed to increase its etching resistance before dry etching with Ar and CF\textsubscript{4} was used to transfer the pattern from the photoresist to the waveguide film.

To study the spectral behavior of the fabricated optical resonant filters, the setup shown in Fig. 4 was prepared. The spatial filter in Fig. 4 is made of a 5-mm focal-length objective and a 60-\(\mu\)m core-diameter fiber and can provide a 0.006 rad of spatial filtering resolution, which is acceptable for characterizing the filter’s normal-incidence spectral behavior separately.

Armed with the theory and the technological set-ups described above, it was possible to control the grating depth (by adjusting the photoresist thickness, the exposure dose, and the etching time) and the waveguide refractive index (by adjusting the forward rf power of the two magnetrons) for the fabricated resonant optical filter. Figure 5 shows the normal-incidence reflection spectra for three different fabricated filters with strong Bragg coupling (left curve) due to relatively deep gratings (160–200-nm depth), weak Bragg coupling (middle curve) due to shallow gratings (30–80-nm depth), and designed Bragg coupling (right curve) due to adjustments of the grating depth (100–140-nm depth) and the waveguide refractive index after observing the normal-incidence reflection spectra of the first two cases.

The second investigated approach was based on spatial modulation of the waveguide effective refractive index \((n^e)\) of the waveguide along the filter plane. This can be realized by modulation of one of the filter physical parameters (waveguide thickness, cladding thickness, if any, grating period, or refractive indices) along the filter plane. We chose to modulate the waveguide effective thickness \((d_{\text{eff}})\) by depositing a nonuniform silica cladding, as shown in Fig. 6. The waveguide effective thickness can be found by accounting for the equivalent optical path after adding the cladding, which results in \(d_{\text{eff}} = d_w + d_c(n_c/n_w)\), where \(d_w\) is the waveguide thickness, \(d_c\) is the cladding thickness at a certain spatial point on the filter surface, \(n_w\) is the waveguide refractive index, and \(n_c\) is the cladding refractive index. To achieve the nonuniform cladding deposition of silica, we used rf sputtering and a cylindrical blocking ring (3-mm high and with 4-mm inner diameter), which was attached to the surface of the fabricated filter. The silica mate-

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**Fig. 2.** (a) Real-time optical monitoring of deposition. (b) Recorded reflection (dashed curve) and best fit (solid curve) when depositing the silica–titania waveguide. (c) The region in the film-refractive-index and the deposition-rate space in which the error of fitting is less than the doubled minimum error.
rial tends to deposit more in the center of the modulated area. The nonuniform cladding deposition modulates the waveguide effective thickness along the filter plan and shifts the resonance wavelength accordingly. The height and the inner diameter of the blocking ring determine the profile of the nonuniform deposition and thus the spatial modulation of $n^*$ along the filter plane. Given a spatial modulation of the waveguide thickness of $d(\rho)$, where $\rho$ is the radius from the center of the spatially modulated area, the normal-incidence resonance profile, $\lambda(\rho)$, can be found by solving Eqs. (2) and (3) for $\lambda(\rho)$ after substituting $n^*$ with

$$n^* = \frac{\lambda(\rho)}{\Lambda}.$$  (13)

Thus, the design of $d(\rho)$ determines the profile of $\lambda(\rho)$ and thus the modification of the filtering window. A better-controlled method for the spatial modulation of $n^*$ can be achieved by spatial modulation of the grating period along the filter plane, which can be realized by electron-beam writing. The drawback of spatial modulation of the $n^*$ method is that the maximum reflection in the filtering window drops, as shown in Fig. 7. Nevertheless, the modification enhanced the bandwidth efficiency and the flatness of the filtering profile, as indicated in Table 1.

The third approach investigated in this paper was a hybrid of the previous two approaches; that is, the two resonance peaks in the strong Bragg-coupling case was widened by the nonuniform cladding deposition. A simple but approximated model for this approach can be obtained by considering that the widening of the filter of strong Bragg-coupling peaks equates approximately to increasing the waveguide optical losses. Consequently, the model that is given by Eqs. (6)–(12) can be used.

4. Results

An optical resonant filter with a close-to-rectangular shape was realized by three approaches. First, the conditions for a resonant filter with strong Bragg coupling were observed, and then the waveguide refractive index was adjusted by changing the mixture of the silica–titania molar ratios to obtain the resonance-peak overlap. The real refractive index

Fig. 3. Computer-controlled photoresist setup for the grating patterning. DUV = deep ultraviolet.

Fig. 4. Optical setup for the optical resonant filter normal-incidence spectral characterization.
changed the splitting gap of the two Bragg peaks, as indicated in Eqs. (1) and (3), whereas the imaginary refractive index determined the width of the resonance peaks, as indicated in Eq. (5). Figure 6 shows the normal-incidence reflection spectra (in decibels) for the modified filter (right curve), the single resonance peak for the weak Bragg-coupling case (middle curve), and the two separated resonance peaks for the strong Bragg-coupling case (left curve). Second, a spatial modulation of the waveguide effective refractive index was performed along the filter plane. This was realized by nonuniform deposition of the waveguide film along the filter plane. Figure 7 shows the reflection before (solid curve) and after (dotted-dashed curve) the modification. Third, a hybrid of the previous two approaches was used. Here the widening realized by the spatial modulation of \( n^* \) was applied to an optical resonant filter with strong Bragg coupling to fill the spectral gap between the two resonance peaks and to cause flatness in the normal-incidence reflection spectra. The fabricated filter was annealed at 500 °C for 1 hr. to reduce the effect of the optical losses in limiting the sharpness of filtering and to promote the widening that is associated with the nonuniform deposition, which controls the resonance-peak widening. Additionally, annealing helps to homogenize the thin films and to stabilize the filter against aging and environmental effects. Figure 8 shows the normal-incidence reflection spectra before (solid curve) and after (dotted-dashed curve) the modification.

To estimate the bandwidth efficiency for the fabricated filters with: Strong Bragg coupling (left curve), week Bragg coupling (middle curve), and designed Bragg coupling (right curve).

### Table 1. Summary of the Bandwidth Efficiency (η) and Flatness (1-δ)
Results for All Fabricated Filters at Passband Losses of 1- and 3-dB Standards

<table>
<thead>
<tr>
<th>Optical Resonant Filter Type</th>
<th>Bandwidth Efficiency η1-dB%</th>
<th>Bandwidth Efficiency η3-dB%</th>
<th>Flatness (1-δ)1-dB</th>
<th>Flatness (1-δ)3-dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weak Bragg coupling</td>
<td>8.5</td>
<td>15</td>
<td>0.834</td>
<td>0.883</td>
</tr>
<tr>
<td>Modified Bragg coupling</td>
<td>12</td>
<td>18.5</td>
<td>0.962</td>
<td>0.980</td>
</tr>
<tr>
<td>Before spatial modulation of ( n^* )</td>
<td>9</td>
<td>16.5</td>
<td>0.860</td>
<td>0.902</td>
</tr>
<tr>
<td>After spatial modulation of ( n^* )</td>
<td>15</td>
<td>23</td>
<td>0.932</td>
<td>0.947</td>
</tr>
<tr>
<td>Hybrid</td>
<td>15</td>
<td>22</td>
<td>0.909</td>
<td>0.925</td>
</tr>
</tbody>
</table>
cated filters, two standards were adopted: a 1-dB loss tolerance in a passband with more than 30-dB losses required in the stop band and a 3-dB loss tolerance in a passband with more than 30-dB losses required in the stop band. Losses are presented with respect to $R_{\text{max}}$. Because of the Fresnel reflection from the first interface, which appears in the reflection spectra background, and the low signal-to-noise ratio of power measurements at the 30-dB scale, we measure the slope of the filter sharpness at a high signal-to-noise ratio and then extrapolate to the 30-dB level to find the required wavelength separation between the two adjacent filtering windows (i.e., channels). For those filters with asymmetric filtering profiles, we calculate the slope at the two sides and then average the corresponding two bandwidth efficiencies. The flatness, which indicates the uniformity of the filter within the passband, was expressed by $(1-\delta)$, where $\delta$ is the average of the squared deviations for all reflection points within the defined passband from the maximum reflection. Table 1 summarizes the bandwidth efficiency ($\eta$) and the flatness $(1-\delta)$ results for all fabricated filters at the two passband-loss standards mentioned above. As shown in Table 1, all three of the approaches enhanced the bandwidth efficiency and the flatness of the fabricated filters.

5. Conclusion
In this work the three proposed approaches resulted in an enhancement of both the bandwidth efficiency and the flatness of the filtering profile. Optical resonant filters can be useful for channel adding and dropping in the field of optical communications. The absence of the sidebands in the profile of optical resonant filters makes them an attractive alternative to, and gives them the advantage over, Bragg filters. Moreover, the close-to-rectangle aspect of their filtering profile results in higher bandwidth efficiency and significantly boosts their potential for more efficient communications.

References