Apodization technique for fiber grating fabrication with a halftone transmission amplitude mask

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Experimental results of fiber Bragg gratings fabricated with halftone amplitude transmission masks and 10-cm-long phase masks are presented for the first time to our knowledge. The performance of the devices is evaluated in terms of their spectral characteristics and deviation from linear group delay. Good out-of-band sidelobe suppression of $-27$ dB and group-delay ripple of $\pm 9.5$ ps is achieved for fully apodized grating devices. © 2000 Optical Society of America

1. Introduction

Fiber Bragg gratings (FBG’s) have proven themselves to be cost-effective fiber-compatible devices for use in optical network systems. They have certain advantages over other passive components such as interference filters or arrayed waveguide technology in that any desired spectral profile and dispersion characteristic can be easily generated by means of controlling the FBG grating pitch, apodization, and device chirp. Precise control of the reflection bandwidth makes FBG’s strong candidates for dense wavelength division multiplexing (DWDM) applications such as channel multiplexers—demultiplexers. When its dispersion characteristic and chirp are tailored, a FBG can be used to compensate for the chromatic dispersion in optical fiber communication networks.2

When a finite-length FBG has a uniform modulation of its index of refraction, the main peak or Bragg resonance ($\lambda_{BR}$) in the reflection spectrum is accompanied by a series of sidelobes at adjacent wavelengths. In DWDM-type applications in which high rejection of nonresonant light is required it is important to lower the reflectivity of the sidelobes, or to apodize the reflection spectrum of the grating.3 Pure apodization results when a tapered cosine or Gaussian index modulation with a constant average index is generated along the length of the device. For chirped FBG dispersion compensators, apodization has the additional benefit of reducing variations or ripple in the spectral group-delay characteristic of the device.2 The presence of delay ripples in a FBG dispersion compensator can impact system performance. Large delay ripple amplitude can cause intersymbol interference resulting in a system eye-opening penalty,4 whereas the delay ripple period, when it is large compared with the signal bandwidth, can result in device dispersion that varies with wavelength.4,5 Several apodization techniques have been developed that are dynamic in nature, such as double-UV exposure2,6 and phase-mask dithering,7 or are static, such as variable-diffraction-efficiency phase masks.8 These techniques ensure that the total average UV exposure along the length of the FBG device is kept constant.

Halftone transmission masks were used previously with UV projection lithography to produce complex surface profiles in photore sist.5,9 The technique has potential for the fabrication of micro-optical elements and other microstructures requiring complex surface profiles. In this paper an UV transmissive halftone mask is used to apodize various FBG devices by variation of the exposure along their length. The potential advantage of halftone mask apodization over dynamic techniques, such as double-UV exposure, which requires a translating beam block, is that, with a uniform UV exposure, the halftone mask defines the dosage per unit length of the device. Uniform fiber illumination can be performed with
either an expanded UV beam\textsuperscript{11} or a scanned UV beam. The comparative ease of halftone mask fabrication makes it attractive when compared with other static apodization techniques such as variable-transmission dielectric mirrors or variable-diffraction-efficiency phase masks. To our knowledge, this is the first presentation of experimental results of apodized fiber gratings made with a halftone mask.

2. Experiment

FBG devices were fabricated by irradiation of hydrogen-loaded Corning SMF-28 fiber with several thousand pulses from a KrF excimer laser operating at a repetition rate of 50 Hz. An incident beam of 1 cm in length was passed through the 10-cm-long halftone mask and then through a 10-cm-long phase mask. To ensure that any nonuniformities in the excimer beam were averaged out, the beam was scanned along the length of the fiber. Two phase masks were used in this study: a uniform-pitch 10-cm-long electron-beam- (e-beam-) written phase mask and a 10-cm-long holographically written chirped phase mask. The e-beam mask was fabricated with a raster-scan e-beam machine to produce a uniform-pitch mask with 2000 fields, each field being 50 \( \mu \text{m} \) in length.\textsuperscript{12} The pitch of the mask was 1.0704 \( \mu \text{m} \). Strong Fabry–Perot resonances were present in the broadband reflection spectrum of the devices made with the mask, indicating the presence of systematic stitching errors. By use of a 10-cm-long uniform-pitch phase mask, extremely narrow-band FBG's can be fabricated. Such long uniform-pitch devices are sensitive to apodization errors along their length and are therefore useful for characterizing the quality of the halftone mask apodization. The second mask was a 10-cm-long holographically written chirped phase mask manufactured by Lasiris with a continuous chirp of 0.11 nm/\( \text{cm} \) and a central mask pitch of 1.0684 \( \mu \text{m} \). FBG devices fabricated with this mask can be used in single-channel chromatic dispersion compensating applications.

Since the irradiation fluences for grating writing are approximately of the same order of magnitude as the ablation threshold of a chrome-on-quartz mask at 248 nm,\textsuperscript{13} it was not possible for the halftone mask to operate in the near field, i.e., in close proximity to the phase mask and fiber. Instead, the halftone mask was used in the far field by use of a beam expansion telescope to reduce the fluence at the halftone mask and then a lens to focus the transmitted beam onto the fiber through the phase mask. When not operating in the near field, the halftone mask produces several higher diffracted orders that are not at normal incidence to the phase mask. These higher diffracted orders would generate index modulations in the fiber that were not normal to the axis of propagation. Such tilted Bragg gratings would result in guided-mode to radiation-mode coupling loss.\textsuperscript{14} An iris was scanned along with the beam to ensure that only the zero-order diffracted beam was incident on the phase mask. A schematic of the UV exposure setup is presented in Fig. 1. The fluence of the beam at the fiber surface was 60 ± 3 mJ/cm\(^2\) per pulse.

We obtained transmission and reflection spectra of fabricated FBG devices by scanning the devices with a probe beam from a tunable laser with a 1-pm wavelength step resolution through a 3-dB coupler. The signal was detected with an optical spectrum analyzer with a 0.05-nm-resolution bandwidth. In this manner the amplified spontaneous emission from the
source beyond the resolution window of the optical spectrum analyzer was removed. The technique used to measure the dispersion characteristic of the devices was described previously. Group-delay spectra of dispersion-compensating FBG devices were obtained with 1-μm wavelength resolution and 1-ps time resolution with 250-MHz signal modulation.

3. Halftone Mask

The halftone masks used in this study were manufactured on a single 150-mm-square, chrome-on-quartz mask plate, with a CORE Model 2564 laser lithography tool. A photograph of a typical halftone mask is presented in the inset of Fig. 1. Each mask consisted of a two-dimensional array of 4 μm × 4 μm unit cells of fixed size, with the variation in transmission being obtained by creation of a window in the chrome layer of appropriate size in each cell. The overall transmission (including all diffracted orders) is thus the window area divided by the unit cell area. When we consider only the zero order, the resultant transmitted power varies as the square of the chrome-free fraction of the unit cell. Two patterns that were used to define the transmission through the halftone mask are presented in Fig. 2. In the low-transmission regions the zero-order transmission was increased in 2.5% increments in a stepwise fashion by variation of the height h and width w of the rectangular windows [case (a) of Fig. 2]. The resultant zero-order transmission was $T = (wh/p)^2$, where $p$ is the pitch or the width of the unit cell. In the high-transmission areas (25–87.9%) the windows were L shaped, resulting in an array of rectangular chrome islands on a clear background. The resultant transmission is $T = (1 - wh/p)^2$, where w and h represent the width and the height of the chrome island, respectively [see case (b) of Fig. 2]. In total there were 36 increments in the transmission. The mask-writing process was constrained by a minimum feature size (line or space) of 1 μm, which had to be taken into account when we defined the shapes of the windows. Figures 3(a) and 3(b) are atomic force microscope (AFM) images of the resultant chrome windows and islands, respectively, which result in the minimum and the maximum transmission, respectively. Since the AFM tip is conical with a diameter of approximately 120 nm, some rounding of the image contours results.

To apodize a FBG device, two transmission masks are required for a particular apodization function. For full apodization the transmission functions are $\cos^2(x)$ and $1 - \cos^2(x)$ [see Fig. 4(a)] where $x$ is position. The first transmission function is used in combination with the phase mask to apply the desired apodization profile to the index modulation, and the second, which has the complementary intensity profile, is used without the phase mask to generate a constant average index along the grating. In general, partial apodization is required for DWDM and dispersion-compensation applications to maximize bandwidth use. For partial apodization the transmission functions $\exp(x^2)\cos^2(x)$ and $1 - \exp(x^2)\cos^2(x)$ were used [see Fig. 4(b)].

Zero-order UV-transmission profiles of the halftone masks were measured with an UV-sensitive p-i-n diode with a 1-mm active area, placed at the center of the iris. The diode and the beam were scanned along the length of the halftone mask. For correct balancing between the apodization function and its complement a constant total UV dose along the device length, which results from the sum of the two exposures, is required.

4. Results

The zero-order UV-transmission profiles of the halftone masks along with the total UV dose are plotted in Fig. 4. For comparison, the corresponding mathematical functions are also plotted. As seen in Fig. 4(a), there is good agreement between the UV-transmitted signal with position and the $\cos^2(x)$ theoretical curve. A 10% deviation of the average index from a constant value along the device length is also observed. In the case of the partial apodization halftone mask [Fig. 4(b)] there exists an imbalance between the apodization function and its complement. This imbalance results in an average index that deviates from a constant value by as much as 40%. Fundamentally, the balancing of the apodization exposure and the complement is limited only by the stepwise nature of the UV transmission through the halftone mask along its length. Rounding errors in the etched rectangular windows and chrome islands of the halftone mask contribute to deviations from the
Fig. 3. AFM images of a halftone mask. (a) Example of a chrome window that results in minimum transmission, (b) example of a chrome island that results in maximum transmission. Since the AFM tip is conical with a diameter of approximately 120 nm, some rounding of the image contours results.
ideal UV transmission profile. The mask used in this study did not take into account these errors. By cross referencing the zero-order UV transmission through the mask at a particular location with the corresponding pixel geometry, we can further optimize the balance between the apodization function and its complement. Although asymmetries near \( \lambda_{Br} \) in the reflection spectrum would result when the present halftone mask is used, it will be shown that this apodization profile imbalance has little impact on the performance of a chirped FBG dispersion compensator.

To characterize the writing setup, an unapodized 100-mm uniform pitch FBG was written with the e-beam-written phase mask as shown in Fig. 1 but with the halftone mask removed. The transmission of the unapodized grating at \( \lambda_{Br} \) was \(-26\) dB. The reflection spectrum of the device is shown in Fig. 5(a). Without any apodization it can be seen that a small amount of asymmetry in coupling near \( \lambda_{Br} \) exists. The higher-reflectivity sidelobes on the long-wavelength side of \( \lambda_{Br} \) are indicative of stronger coupling at the ends of the grating as opposed to the center. Since the fiber was suspended horizontally in a holder, under a small amount of tension, it is likely that a small amount of fiber sag contributed to a slight misalignment at the center of the grating as compared with the ends.

A fully apodized uniform pitch FBG of 100 mm in length was written with the \( \cos^2(x) \) apodizing halftone mask and its complement under identical exposure conditions. The transmission of the device at \( \lambda_{Br} \) was \(-26\) dB, whereas the 3-dB bandwidth in reflection was \( 58\) pm [see Fig. 5(a)]. Along with the small amount of systemic overcoupling on the long-wavelength side of \( \lambda_{Br} \), an additional sidelobe was visible \( 30\) pm on the short-wavelength side, which is due to the 10% deviation of the average index from unity along the device length. In spite of the asymmetry in \( \lambda_{Br} \), good apodization was achieved with sidelobe suppression of \( 27\) dB \( 0.1\) nm away from \( \lambda_{Br} \).

A partially apodized device \( \exp(x^2)\cos^2(x) \) was written under the same conditions, resulting in \(-35\) dB transmission and a 3-dB bandwidth of \( 41\) pm [Fig. 5(b)]. The imbalance between the apodization function and its complement generates sidelobes on the short-wavelength side of \( \lambda_{Br} \). We modeled the spectral response of the partially apodized device by taking into account the UV transmission profiles through the halftone masks and assuming an index modulation \( \Delta n = 4.5 \times 10^{-5} \). The e-beam mask was simulated by means of incorporating a random stitch error of \( 5 \pm 2.5\) nm between each of the 2000 fields.
Fiber nonuniformity variations in fiber photosensitivity as a result of UV exposure and outdiffusion of hydrogen were not considered. As shown in Fig. 5(b), there is good agreement between the simulated and the actual responses.

The two sets of apodization masks were then used in conjunction with the chirped holographic phase mask to produce single-channel chromatic-dispersion-compensating devices. The transmission and the reflection spectra of a fully apodized \[\cos^2(x)\] dispersion-compensating FBG is presented in Fig. 6(a). The transmission of the device is \(-12\) dB at \(\lambda_{Br}\), and the 1-dB reflection bandwidth is 0.324 nm.

The measured dispersion over the 1-dB reflection bandwidth of the device was 780 ps/nm and is presented in Fig. 6(b). Standard single-mode optical fiber has a dispersion rate of 17 ps/(nm km); therefore the fully apodized device could compensate for fiber dispersion over 45 km. The deviation in linear phase delay (group-delay ripple) over the 1-dB bandwidth is presented in Fig. 6(c). Excellent group-delay ripple response is seen with a peak-to-peak ripple amplitude of \pm 9.5 ps. This result is consistent with similar devices made with the double-UV exposure technique. If such a device were placed into a network system with a 10-Gbit/s bit rate, the worst-case eye-opening penalty would be 0.5 dB. Other groups have reported similar group-delay ripple performance of similar length gratings used for dispersion compensation.

With the second set of halftone masks, a partially apodized chirped FBG was fabricated with a transmission at \(\lambda_{Br}\) of \(-9\) dB and 1-dB bandwidth in reflection of 0.84 nm. The transmission and the reflection spectra are presented in Fig. 7(a). In spite of the imbalance between the apodization function and its complement, the low-reflectivity chirped device showed little asymmetry near \(\lambda_{Br}\) in the reflection spectrum. This is in contrast to the high-reflectivity uniform-pitch grating in Fig. 5(b). We modeled the spectral response of the chirped device, taking into account the UV transmission profiles through the partially apodizing halftone masks, assuming an index modulation \(\Delta n = 1.25 \times 10^{-4}\), and using the holographic phase mask chirp rate and central pitch. The responses are presented in Fig. 7(a). Since the phase mask used was holographic, no stitch errors were incorporated into the model. There is good agreement between the spectral responses of the device and the model.

The linear dispersion of the device over the 1-dB reflection bandwidth is 675 ps/nm and is presented in Fig. 7(b). Such a device could compensate for fiber dispersion over 40 km but over a broader bandwidth than the fully apodized device. The deviation from linear phase delay is presented in Fig. 7(c) with a peak-to-peak spectral-delay ripple amplitude over the 1-dB bandwidth of \pm 14 ps and a slowly varying second-order deviation as great as 20 ps at the bandwidth edges. The peak-to-peak ripple is similar to the \pm 10-ps spectral-delay ripple amplitude obtained with the same phase mask with the double-exposure photoimprinting technique that was reported previously. The simulation group-delay ripple response that incorporates the variable average index in the apodization with position is also presented in Fig. 7(c). The variable average index generates the same deviation-from-linearity envelope response. As is borne out in the model, the imbalance in the apodization profiles results in a different dispersion slope of the device near the bandwidth edges. When we consider a 10-Gbit/s system, the period of the slope deviation or bow in the group-delay response is much larger than the signal modulation and thus would not contribute significantly to the overall eye-opening.

![Figure 6](image-url)
penalty. The peak-to-peak ripple amplitude of ±14 ps would contribute a worst-case eye-opening system penalty of 0.7 dB.17

5. Conclusions

We have presented what to our knowledge is a new variation on the double-exposure photoinprinting technique, which uses a halftone transmission mask to fabricate fiber Bragg grating (FBG) devices. Good out-of-band sidelobe suppression is achieved for fully apodized devices. Fully apodized single-channel dispersion-compensating FBG’s were also made that exhibited excellent peak-to-peak spectral-delay ripple performance over the 1-dB bandwidth of the devices. In spite of an imbalance between the partial apodization function and its complementary intensity profile, good apodization and peak-to-peak ripple amplitudes in the group-delay response of partially apodized dispersion compensators were achieved.

References


15. S. Ryu, Y. Horiuchi, and K. Mochizuki, “Novel chromatic dis-
