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Research Report

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Abstract **-** We report on the fabrication by electron-beam lithography of Bragg gratings, which serve as wavelength-selective elements of a Mach-Zehnder type add-drop filter. To meet telecommunication network requirements, the gratings must have about 20,000 lines, corresponding to a length on the order of 10 mm. Furthermore, the coupling strength of the gratings has to be varied according to a bell-shaped taper function to suppress unwanted side lobes in the gratings' reflection spectra. We have realized coupling coefficient variation at constant etch depth by changing the duty cycle along the grating. The employed pattern reversal process provides good line-width control of the grating ridges down to 50 nm, and good coverage by the subsequent PECVD overgrowth. Optical measurements are presented that prove the excellent performance of the grating couplers.

1. Introduction

Wavelength division multiplexing for telecommunication purposes requires wavelength-selective filters for adding and dropping a single wavelength channel. These functions can be well performed with Bragg gratings etched into waveguide structures, and combined to yield a Mach-Zehnder add-drop filter (see figure 1). The waveguides can be made from silicon oxy-nitride (SiON) structures sandwiched between two silicon dioxide (SiO_2) cladding layers. The incoming signals on 40 channels, with around 1545 nm wavelength and 0.8 nm channel spacing, are split into the two waveguides by directional couplers. The two branches have identical Bragg gratings etched into the waveguide material that reflect the resonant channel into the drop port. All other channels continue into the through port, and the empty frequency can be reused to transport a new signal introduced via the add port. The wavelength selectivity of the thus-established add-drop filter is determined solely by the Bragg gratings. The interferometer is merely responsible for the routing of the reflected drop signal into a separate waveguide. In order to perform this routing both arms must have an identical optical path length, which is ensured by post-fabrication trimming with heaters or by UV exposure of one of the interferometer waveguides.

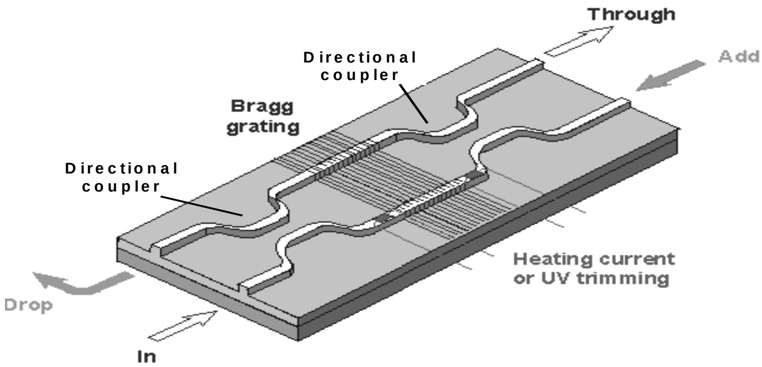
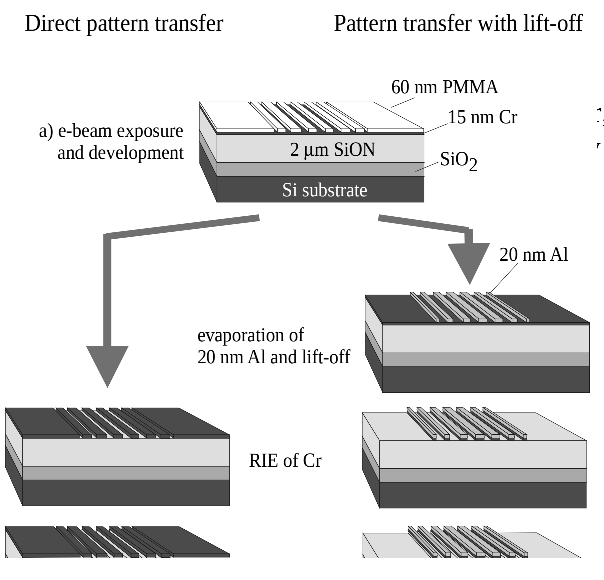


Figure 1: Schematic view of a Mach-Zehnder type add-drop filter.

2. DESIGN CONSIDERATIONS

The Bragg gratings have to fulfill stringent requirements to be suitable for telecommunication purposes. First, the spectral width of the reflection peak has to comply with the channel distance of 0.8 nm. This is achieved by an average coupling coefficient on the order of 10 cm^{-1}. Second, the reflection of the grating has to be sufficiently strong to ensure low *intra*-channel crosstalk. With the predetermined average coupling coefficient, this can only be achieved by using a long grating. For *intra*-channel crosstalk lower than –30 dB, about 20,000 grating lines corresponding to a grating length on the order of 10 mm are required. Third, only the desired channel should be dropped to avoid *inter*-channel crosstalk. A uniform grating with a constant coupling coefficient along the grating, however, exhibits undesired side lobes in the reflection spectrum, resulting in a partial dropping of the other channels. The required suppression of the side lobes in the reflection by more than –20 dB can only be achieve
decreasing the coupling strength near the ends of the gr

The coupling strength of surface-corrugated Bragg
ence in refractive index between the core and the cladd
cle (DC) of the grating structures. The coupling strengt
to keep the etching process simple and, more important
preferred. Sakata [2] suggested the use of coupling stre
the fabrication of the first apodised Bragg gratings cou



The manufacture of such gratings with continuously varying line width is a challenging task for standard electron-beam lithography tools. First, the gratings are extremely sensitive to stitching errors. Second, the line width can usually only be set in certain increments corresponding to the pixel size of the pattern generator, which will result in a coarse gradation of the duty cycles and thus limit the smoothness of the apodisation. Third, the variation of the duty cycle results in different effective refractive indexes along the grating. In order to keep all parts of the grating in resonance for the same frequency, the grating period has to be tuned by a fraction of one percent. Such fine changes in the grating period are not possible with most standard pattern generators.

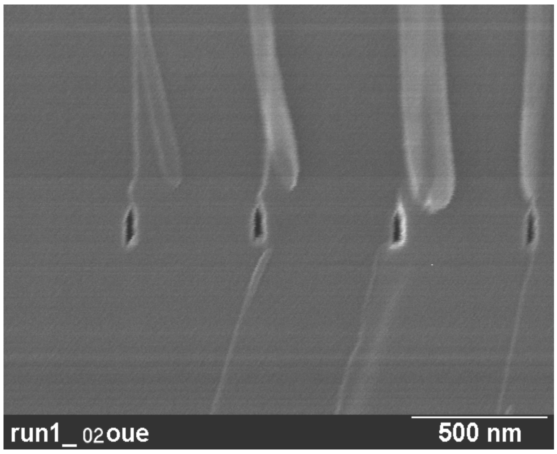


Figure 4: Cross section of a SiON grating with narrow grooves (50 nm) after PECVD overgrowth with the SiO_2 upper cladding. Although the two materials display no contrast, a series of voids indicates the position of the grating trenches.

We used a LION-LV1 electron-beam lithography system (Leica Microsystems Jena) at 2.5 keV electron energy to manufacture various apodised Bragg gratings. The unique combination of features of this system make it particularly suited to our application: (i) the option of working at low electron energies greatly reduces proximity effects. (ii) Its continuous path control (CPC) exposure mode avoids all field stitching and allows a placement accuracy of 2.5 nm. (iii) Every grating line can be exposed with an individual focus setting of the electron beam, which allows a continuous variation of the line width and thus DC [3]. Various grating patterns with a pitch of 523 nm and up to 10 mm length were exposed using this method.

Obviously, the coupling strength cannot completely go to zero at the end of the gratings as this would require infinitely small structures in the surface corrugation. Thus, we experimentally determined the accessible DC range as described in the next section. The taper functions used were then optimized numerically under these technological boundary conditions.

3. FABRICATION PROCESS

In principle, varying the duty cycle from 50% to larger or smaller values has the equivalent effect of reducing the coupling strength. However, gratings with exposure DCs close to 1 are very unfavorable: (i) the total exposed area is greater and thus the exposure time is much longer, (ii) due to forward scattering in the resist layer, a significant undercut in the resist profiles causes narrow remaining resist lines to collapse. We therefore used only the DC range below 0.5. To investigate gratings apodised using narrow ridges (and wide grooves) as well as wide ridges (and narrow grooves), we employed two alternative pattern transfer processes depicted in figure 2. The Bragg- grating-based add-drop filters were implemented in the high-refractive-index contrast SiON technology developed at the IBM Zurich Research Laboratory [4]. We have incorporated the grating fabrication after having deposited the SiON waveguide core by PECVD. For electron-beam lithography a 15-nm-thick Cr layer and a 60-nm-thick PMMA resist layer were deposited to avoid electrostatic charging.

After electron-beam exposure and development, the pattern was transferred by reactive ion etching (RIE) to a depth of 70 nm into the SiON waveguide. Whereas the direct pattern transfer leads to grooves corresponding to the exposed lines, the second process using a lift-off step inverts the pattern, which causes ridges. After the grating has been defined, the waveguide ridges were etched by RIE and overgrown with a SiO_2 cladding layer. Further details about the waveguide fabrication process can be found elsewhere [4].

Figure 3 shows different grating duty cycles etched into SiON with the pattern reversal process before overgrowth. In general, both processes led to SiON structures of similar quality. However, we found that the PECVD overgrowth of gratings with narrow grooves to form the upper cladding resulted in air pockets. Figure 4 shows a cross section of an SiON grating with 50-nm-wide grooves after overgrowth. The significant difference in refractive index of the voids and that of the waveguide material resulted in a huge coupling strength. Therefore only gratings fabricated with a tone reversal by lift-off were operational.

4. MEASUREMENTS

The optical performance of the Bragg gratings was measured with an optical spectrum analyzer [5]. The transmission and reflection spectra shown in figure 5 exhibit a reflection of greater than 99.9% (–30 dB transmission dip) over 0.22 nm.

The reflection signal of uniform and apodised gratings are depicted in figure 6. The apodised grating has an excellent suppression of better than 20 dB outside a bandwidth of 1.36 nm, whereas a uniform grating

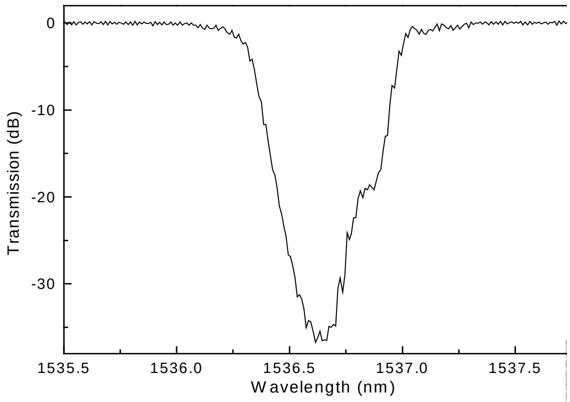


Figure 5: Measured transmission spectrum of an apodised Bragg grating.

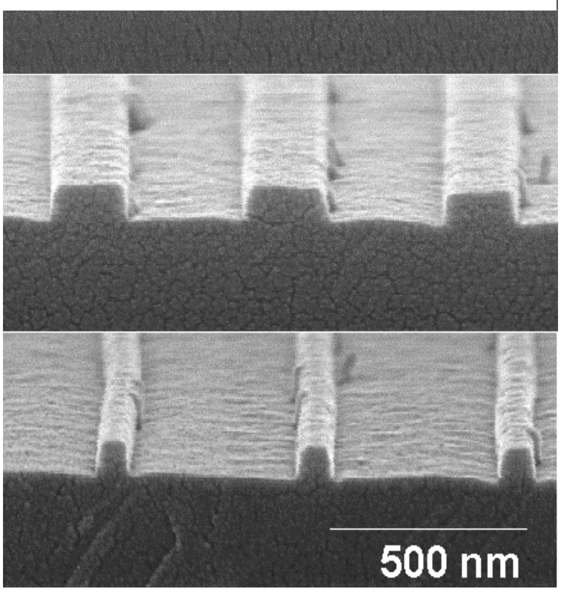


Figure 3: Cross section at three different positions along the same SiON Bragg grating with three different duty cycles (from top to bottom 50%, 38%, and 16%). Grating period: 523 nm, etch depth: 70 nm. The grating was fabricated using the tone reversal process (see figure 2, right column).

with the same dimensions has only 10 dB suppression outside the same bandwidth, which allows a channel spacing of 0.8 nm. The full width for a side-lobe suppression of better than –20 dB amounts to 3.8 nm for the uniform grating, which is nearly three times the value for the apodised grating.

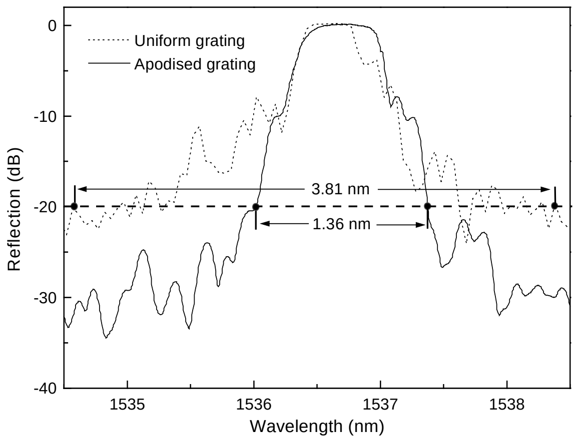


Figure 6: Measured reflection spectrum of an apodised and a uniform Bragg grating.

5. CONCLUSIONS

We have presented a method for fabricating apodised, surface-corrugated Bragg gratings by electron-beam lithography. The apodisation was achieved by varying the focal setting of the electron beam and thus controlling the grating duty cycle. The optical characterisation proves that these gratings comply with the demands of wavelength division multiplexing with 100 GHz channel spacing when combined with a Mach-Zehnder interferometer to yield an add-drop filter.

Mass production of such devices would require a faster method for pattern definition. For this purpose, novel replication techniques such as microcontact printing [6], or hot embossing lithography [7] using electron-beam-generated masters may provide rapid means of grating manufacture.

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