Interleaved Sampled Bragg Gratings With Concatenated Spectrum

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***Abstract*—We design and demonstrate interleaved sampled Bragg gratings with concatenated spectrum which produce high channel counts with simple design and fabrication. These gratings can be applied in multichannel filtering, dispersion compensation, and many other functions. The devices were implemented as reduction-photolithographically written anti-symmetric Bragg gratings.**

***Index Terms*—Gratings, integrated optics, optical communication.**

I. INTRODUCTION

SAMPLED Bragg gratings (SBGs), originally proposed for multichannel semiconductor lasers [1], have many important applications in areas involving multichannel multiplexing and demultiplexing [2], [3], dispersion compensation [4], metrology [5], and repetition rate multiplication [6], [7]. A disadvantage inherent in conventional amplitude-SBGs is their reduced strength compared with that of an unsampled Bragg grating. Physically, the strength reduction occurs because much of the total grating length is replaced by empty waveguide. To compensate for the addition of empty space in the grating, an increase in the index modulation in the remaining grating portions is required and this increase is proportional to the number of spectral peaks, which we refer to as channels N_c introduced by the sampling process. The use of interleaved SBGs (ISBGs), [3]–[5] which eliminates empty regions within the grating has been shown to partially compensate for lost reflective strength and thus reduce increases in index modulation required to preserve reflective strength. We note that phase SBGs [8] have also been employed to mitigate loss in reflective strength.

In Fig. 1(a), we show the spatial profile of a simple SBG, an SBGs interleaved according to the original proposal [3], [4]. In this figure, $\Delta\lambda$ is the spectral spacing of peaks for individual SBGs and $d\lambda$ the spectral separation of peaks of the ISBGs. To the best of our knowledge, however, there has been no experimental demonstration of this type of ISBG to date. One important reason is the difficulty in interleaving SBGs without affecting the spectrum of each SBG.

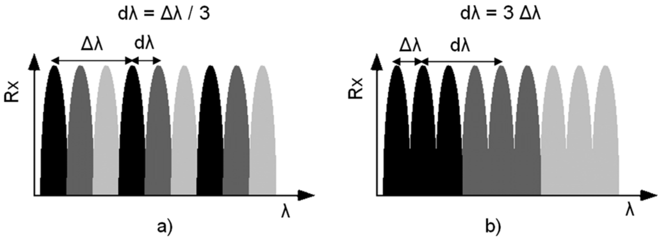

Fig. 1. Reflection (Rx) of ISBG with (a) interleaved spectrum and (b) concatenated spectrum.

In this letter, we analyze and experimentally demonstrate the conditions for a novel approach for interleaving SBGs. In our scheme, the spectra of individual SBGs are concatenated rather than interleaved [see Fig. 1(b)]. This produces an ISBG with a broader and flatter spectrum without the need of apodization. This approach requires an increase in the index of modulation proportional only to $N_c^{0.5}$ identical to the requirement for pure phase sampled gratings [8]. However, concatenated spectrum ISBG (CS-ISBG) has no need for multiple phase shifts as required with pure phase sampled gratings. Also, the design can be intuitively explained from the couple mode equations [9] without the need of optimization algorithms [8].

For experimental demonstration, we use the anti-symmetric waveguide grating [10], [11] fabricated with the line-by-line control using deep ultraviolet (DUV) photolithography which adds the functionality of separating the input and output of the ISBG without the need of circulators. To the best of our knowledge, the present work constitutes the first demonstration of an CS-ISBG.

II. DESIGN OF CS-ISBG

Interleaving a series of SBGs with closely spaced center wavelengths can modify the individual grating spectra and, therefore, produce distortion in the resultant ISBG spectrum. Fabrication can also be difficult when abrupt changes at the interface between different grating elements are required.

In the proposed scheme, M SBGs are placed without phase shifts and with a fixed periodicity L_s, as shown in Fig. 2.

In this figure, Λ_i is the period of the ith SBG obtained from $\Lambda_i = \lambda_i/2n_{\mathrm{eff}}$, where λ_i is the Bragg central wavelength of the ith SBG and n_{eff} the effective index. The wavelength spacing produced in each of the individual SBGs can be assumed to be similar and given by $\Delta\lambda \approx \lambda_c^2/(2n_{\mathrm{eff}}L_s)$ [1], where λ_c is the average of the central wavelengths of the M SBGs.

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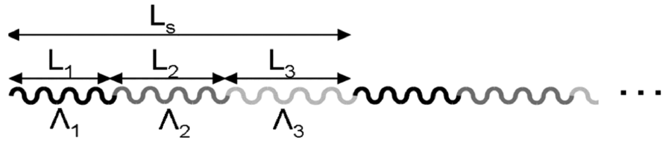

Fig. 2. Basic structure of CS- ISBG with $M = 3$ grating elements.

At the interface of each adjacent grating the phase is zero, which eliminates subperiod features and undesired resonances. This type of interleaving SBG produces the following equivalent sampling function for the ith SBG

$$s_i(z) = \mathrm{rect}\left(\frac{z - L_i/2}{L_i}\right) \otimes \sum_m \delta(z - mL_s) e^{-j2\pi m \frac{\mathrm{mod}(L_s,\quad \Lambda_i)}{\Lambda_i}}$$

where mod (x, y) is the modulus after division between x and y, and $\otimes$ is the convolution operation. The phase term is inherent in this proposed modified sampling process. However, it does not produce special requirements during fabrication, only repetition of the gratings is involved. Nevertheless, the phase term can produce displacement in the resonant peaks and strength variations as can be obtained from the coupling coefficients

$$|k\_ac_i(n)| = k_o \frac{L_i}{L_s} \left| \sin c \left(\left(n - \frac{\mathrm{mod}(L_s, \Lambda_i)}{\Lambda_i} \right) \pi \frac{L_i}{L_s} \right) \right|.$$

When $\mathrm{mod}(L_s, \Lambda_i) \sim 0$, the maximum reflection of the ith SBG occurs at $\lambda_i(n = 0)$ and the first zero in the sinc function at $n = L_s/L_i = M$. Distortion of the spectrum of each SBG can occur when $\mathrm{mod}(L_s, \Lambda_i) \neq 0$. For example, when $\mathrm{mod}(L_s, \Lambda_i) = 0.5\Lambda_i$, the reflection is minimized at $\lambda_i(n = 0)$ and there are no other zeroes for any n.

To obtain similar $k\_\mathrm{ac}_i(n)$ functions and smooth transitions between adjacent gratings, it is required that $L_i = N\Lambda_i$, where N is an integer representing the number of grating periods within L_i. Since L_i is greater than 200 μm, N is at least 400 for our operating wavelengths. This produces variations among similar order coupling coefficients of adjacent SBGs lower than 0.25%.

For a set of nonapodized M SBGs, we propose to use the separation between center wavelengths of adjacent SBGs $d\lambda$ equal to $M\Delta\lambda$. At this separation, the position of maximum and minimum reflection peaks of adjacent gratings coincide. Since each unapodized SBG can produce $\sim M$ useful channels, the set of M SBGs produces $\sim M^2$ channels. It can be mathematically demonstrated that operating at this $d\lambda$ value yields $\mathrm{mod}(L_s, \Lambda_i)/\Lambda_i < 0.2$, when $N >> M$, a condition that reduces distortion and strength variations. In this letter, numerical simulations based on coupled-mode theory and transfer matrix methods [9] are used to show our proposed scheme.

Fig. 3 shows the calculated spectra for $M = 3$ CS-ISBG. The total length of the CS-ISBG is $L_t = 19$ mm. Other parameters are: $k_o \sim 400$ m^{-1}, $L_s \sim 1200$ μm, $L_i \sim 400$ μm, and $N = 764$. This figure shows the match of center wavelengths of SBG1, SBG2, and SBG3 (arrows) with the zeroes of the adjacent SBGs. Up to nine useful channels are obtained.

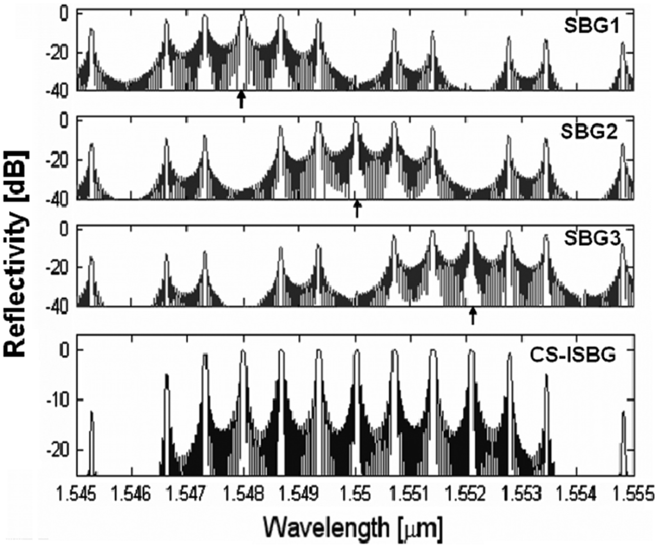

Fig. 3. Simulated reflection spectra of three individual SBGs and the concatenated spectra obtained by coherent addition.

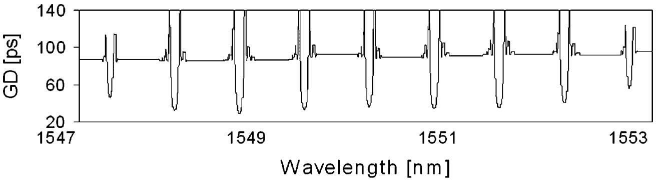

Fig. 4. Group dispersion (GD) of designed $M = 3$ CS-ISBG.

Group dispersion for the case $M = 3$ (Fig. 4) has a variation between central wavelengths of adjacent SBG of ~4 ps. This variation is due to the temporal separation among adjacent SBG $2n_{\mathrm{eff}}L_g/c$, where c is the speed of light. Modeling (not presented here) indicates that dispersion compensation can also be achieved without modifying the principle of placing maximum and minimum of adjacent gratings as proposed in this letter.

To avoid distortion in the CS-ISBG spectrum it was found that variations in λ_i should be $<0.2 \times \Delta\lambda$. For the designed gratings ($\Delta\lambda \sim 0.67$ nm) this requires fabrication tolerances on the order of 50 nm.

Fig. 5 shows the minimum product k_oL_t to provide at least $N_c = M^2 - 2$ channels with less than 2-dB variation in strength. Higher values of k_oL_t provide up to M^2 channels with less than 1-dB variation. It can be seen in that figure that the required increment in k_oL_t is linear with M. The number of channels N_c, however, increases proportionally to $\sim M^2$. The bandwidth variation $(S \cdot D)$ in the $M^2 - 2$ channels is $<10\%$.

III. FABRICATION AND CHARACTERIZATION

A device was fabricated in silica-on-silicon using an anti-symmetric Bragg grating [10], [11] to verify the CS-ISBGs. The anti-symmetric grating integrated with asymmetric y-branches provide the required filtering and separation between incoming from outgoing signals without the need of circulators. This functionality was recently demonstrated using unsampled Bragg gratings [10], [11]. While demonstrated

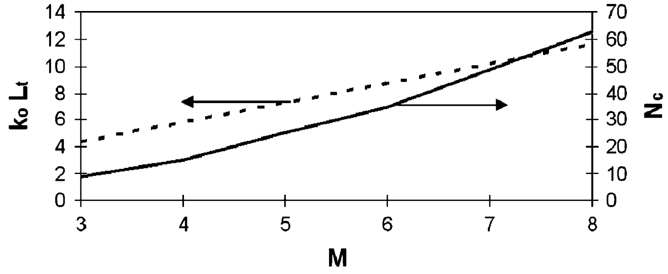

Fig. 5. k_oL_t (dotted lines) and N_c (solid lines) as a function of M.

Fig. 6. Basic structure of anti-symmetric CS-ISBG.

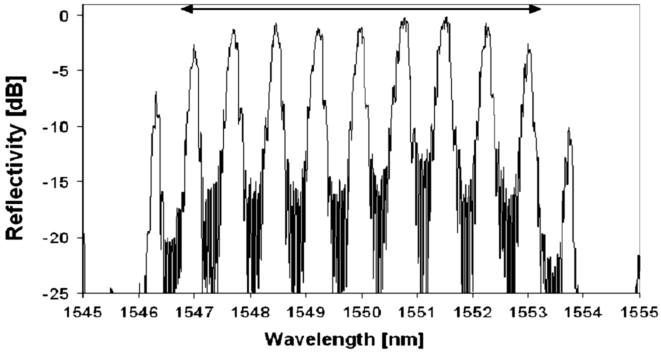

Fig. 7. Spectrum of the CS- ISBG (normalized to the maximum value).

here with integrated optics, implementation using fiber Bragg gratings is also feasible. We note, however, that the DUV photolithographic fabrication approach utilized provides powerful capability to control all details of grating line placement with high precision.

The CS-ISBG shown in Fig. 6 has $M = 3$ sections, $L_1 \sim L_2 \sim L_3 \sim 400\ \mu$m, with $L_t = 19.2$ mm. The designed periods were $\Lambda_1 = 0.534, \Lambda_2 = 0.535, \Lambda_3 = 0.536\ \mu$m and $L_s \sim 1200\ \mu$m. The separation of the asymmetric y-branches at the edge of the device is 127 μm to allow coupling with fiber arrays.

Reflection spectra were measured using a tunable laser and an optical spectrum analyzer with a resolution of 0.01 nm. A polarization controller allowed characterization of both the TE and TM modes. A fiber array was used to couple light into and out of the device.

Fig. 7 shows the TM normalized reflection spectrum of the ISBG when power was launched in the narrow branch. The ISBG exhibited nine useful channels (under the line) as expected from the design $M = 3$. The three center wavelengths of individual SBG were measured, respectively, as 1547.72, 1550, and 1552.28 nm. Dips in the transmission spectrum around ~13 dB indicated $k_oL_t = 5.5$. The variation in the reflection strength was measured as ~2.35 dB which is slightly higher than the expected value (2 dB).

The TE spectrum (not shown here) has a shift in all the Bragg wavelengths of ~0.21 nm with similar strength and shape. This polarization dependence can be reduced as discussed in [12]. The dispersion properties for each channel are similar to a conventional Bragg grating of similar length. Insertion loss of 8 dB was obtained for TE and TM polarization including the coupling losses. The sidelobes of each resonant peak can be reduced by applying apodization using techniques demonstrated in [13].

IV. SUMMARY

We have designed and experimentally demonstrated interleaved Bragg gratings with concatenated spectrum. These devices can increase the channel count at constant reflectivity provided that the grating coupling constant increases as $N_c^{0.5}$, as in pure phase SBGs, while allowing simpler and intuitive design and fabrication compared with phase SBGs. Applications of this type of ISBG in multichannel multiplexers, metrology, and dispersion compensation are among other potential applications. From modeling, 64 channels were obtained without distortion. The CS-ISBG was demonstrated in silica-on-silicon using anti-symmetric Bragg gratings.

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