Control of light transmission in laser-written phase-shifted Bragg grating couplers

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We demonstrate the fabrication by direct laser writing and the operation of a directional coupler containing Bragg gratings in each waveguide. We achieve high-precision control over the longitudinal shift between the gratings, which feature first-order Bragg resonance at telecommunication wavelengths. We observe fundamental differences between light transmission characteristics in couplers with unshifted and shifted gratings in agreement with theoretical predictions. © 2011 Optical Society of America

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The use of ultrafast lasers to inscribe optical waveguide devices in transparent glasses or other media, the so-called direct-write technique, attracts considerable attention as evidenced by several recent review articles [1–4]. The technique uses a tightly focused femtosecond laser beam that is scanned through the medium, and the high-intensity focal spot initiates nonlinear processes leading to a permanent refractive index change in the glass. The ultrafast direct-write technique is a flexible and cost-effective tool that is also capable of fabricating three-dimensional photonic structures.

Direct-write processing is routinely used to create micrometer-scale structures that have a continuous morphology; however, it is seldom considered to be a compatible technique when submicrometer feature size and phase control of the order of the wavelength of light is required. A factor contributing to this oversight arises from the belief that the feature size is limited by the focal spot size of the laser, typically $>5\,\mu$m in diameter. In fact the highly nonlinear nature of the method has enabled first-order waveguide Bragg gratings (WBGs) with a modulated index variation with a period of ≈500 nm and smaller [5,6]. In those demonstrations the WBGs were written in a single pass of a modulated laser beam through a glass sample, and the high fidelity of those gratings reflects the excellent *relative* phase control of the high-precision motion control stages available today. However, the fabrication of sophisticated photonic circuitry requiring *absolute* phase control between multiple components, such as Bragg grating couplers used for add–drop multiplexing [7–16], remains a challenging problem for direct-write methods.

In this Letter, we report on the first direct laser writing of WBG couplers with accurate (submicrometer resolution), absolute control over the grating shift using sophisticated motion control and optical metrology validation systems. We demonstrate the high precision of the written structures by measuring their transmission spectra, which clearly show the characteristic influence of the phase shift, in good agreement with theoretical predictions.

The experimental setup and WBG fabrication techniques used in this work are outlined in [17]. Bragg grating couplers were fabricated in a $L = 4.52$ mm long Corning Eagle2000 borosilicate glass that was translated at $25\,\mu$m/s through the laser beam (focused $170\,\mu$m below the surface of the glass). WBGs formed by segments of exposed glass with approximately $\Lambda = 500$ nm resulted in a first-order Bragg resonance at 1551.05 nm. The grating contrast is close to a sinusoidal modulation, and the index change extends over the complete waveguide width of $12.8\,\mu$m. The refractive index contrast between the WBG and the surrounding glass sample is 2.6×10^{-3}, estimated from the measured mode field diameter and matching it to beam propagation simulation theory. The Bragg reflection bandwidth measured for a single grating is $\Delta\lambda = 0.3$ nm, which corresponds to the grating contrast of 2.7×10^{-4}. We aim to fabricate couplers with a specific shift (φ) between the WBGs as illustrated in Fig. 1(a). The phase shift between two WBGs is created by delaying the modulated interrupt trigger signal to the regenerative amplifier's Pockels cells for only one of the WBGs by the required amount. Two types of couplers are written with symmetric and antisymmetric Bragg gratings corresponding to zero shift or half a period shift. This phase shift was verified and monitored in real time using a Renishaw metrology laser-interferometer system, which precisely measured the exact position of every refractive index perturbation in both WBGs. The micrographs of fabricated symmetric and antisymmetric couplers presented in Figs. 1(b) and 1(c) confirm the absence of shift and half a period shift between the WBGs, respectively. To characterize the transmission characteristics of the fabricated couplers, we use a continuous wave source from a swept wavelength system and fiber-couple it into the first waveguide. We then measure the output transmission spectrum from each waveguide using a fiber-coupled spectrum analyzer, as shown schematically in Fig. 1(d).

We first perform measurements at wavelengths substantially detuned from the Bragg resonance, i.e., we consider $\lambda < 1550.5$ nm or $\lambda > 1551.5$ nm. In these

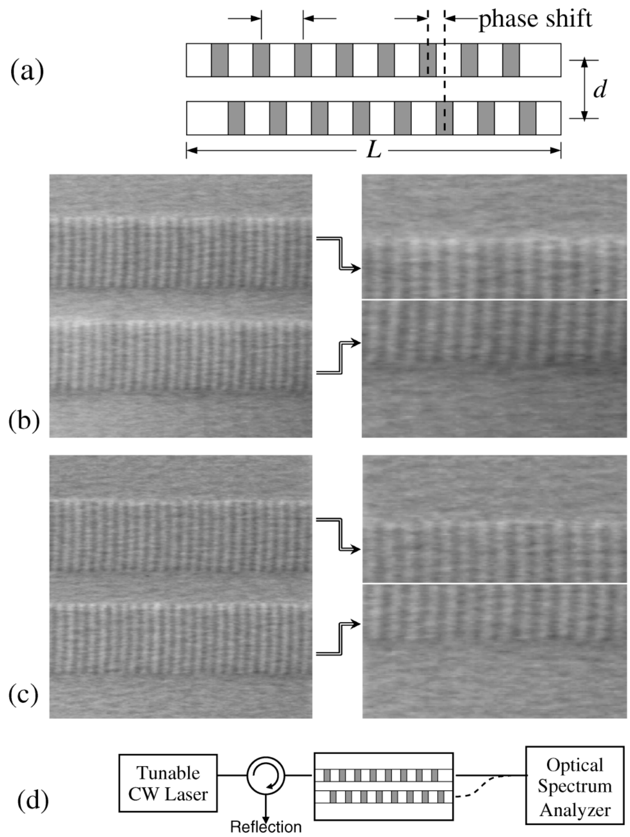

Fig. 1. (a) Schematic of the Bragg grating coupler. Transmission differential interference contrast micrographs of (b) symmetric and (c) antisymmetric Bragg couplers. The 500 nm grating pitch is clearly visible in the horizontal direction while the vertical scale has been compressed by a factor of 4 for clarity. (d) Bragg grating coupler characterization setup.

wavelength ranges, the grating does not have any significant effect on the propagating waves since the Bragg condition is not satisfied. The guided modes effectively experience the longitudinally averaged refractive index in each of the waveguides. Accordingly, there should be no differences between structures with different grating shifts. Indeed, our measurements confirm that the transmission properties of couplers with symmetric and antisymmetric grating configurations almost coincide for each pair of samples with a particular separation d. Since the device effectively operates as a conventional directional coupler at these wavelengths, its transmission (in the absence of losses) can be described by the classical expressions; specifically, the output intensity at the input waveguide is $I_1 = \cos^2[(L/L_c)(\pi/2)]$, and at the second output waveguide $I_2 = \sin^2[(L/L_c)(\pi/2)]$. Here L_c is the coupling length, whose value decreases (i.e., coupling increases) as the waveguides are brought close together. We perform transmission measurements for a set of different separations d and establish that for $d = 20\,\mu$m there is strong coupling between the waveguides as 80% of light is transmitted through the second waveguide at the output, which corresponds to $L_c \simeq 1.4L \simeq 6.33$ mm. We select this coupler to further investigate the transmission properties under Bragg-resonant conditions.

Before proceeding to the analysis of the experimental measurements at Bragg resonance, we present results of numerical simulations based on the coupled-mode equations [18,19] to highlight the key expected features of the transmission characteristics. The light propagation in the directional coupler can be explained as a beating of eigenmodes of two coupled waveguides, and we show their dispersion in Figs. 2(c) and 2(d). In a symmetric structure, eigenmodes are composed of counterpropagating even or odd supermodes of coupled waveguides, whereas in the antisymmetric case the eigenmodes are formed by even (odd) forward modes coupled with odd (even) backward modes. The gray shading is used to mark the Bragg reflection gaps, corresponding to a range of wavelengths where both eigenmodes exhibit evanescent decay inside the structure leading to strong reflection. Note that the mode dispersion and their group velocities [Figs. 2(e) and 2(f)] are strongly affected by the longitudinal shift between the gratings, leading to pronounced distinctions in transmission characteristics shown in Figs. 2(g) and 2(h).

We now test experimentally the transmission for the symmetric and the antisymmetric grating configurations, as presented in Fig. 3. We observe a good agreement between the key features of the calculated and measured transmission curves; cf. Figs. 2(g), 2(h), 3(c), and 3(d). In particular, in the symmetric structure, the ratio of output intensities in the first and second waveguides is strongly wavelength dependent; see Figs. 2(g) and 3(c). This occurs because the even and odd eigenmodes have spectrally shifted Bragg gaps [11,12,14] [see Fig. 2(c)], and as a result the relative reflection of eigenmodes

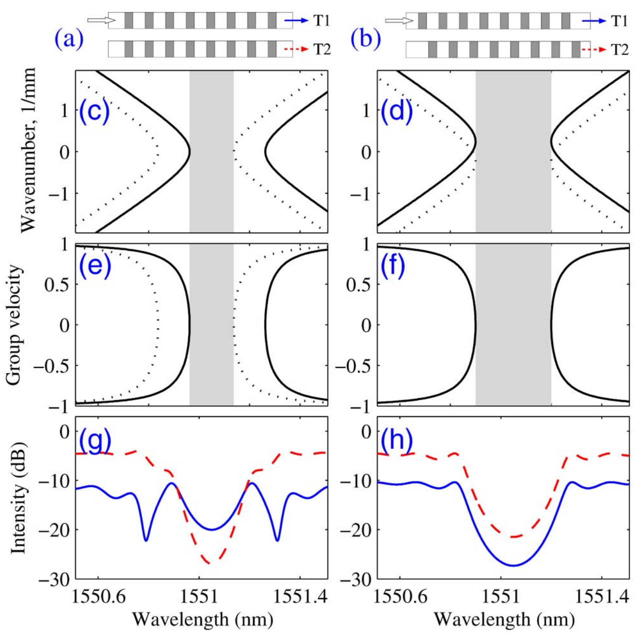

Fig. 2. (Color online) Numerical analysis for (a), (c), (e), (g) symmetric and (b), (d), (f), (h) antisymmetric couplers. (a) ,(b) Schematic of the coupler geometry. (c), (d) Dispersion (wavenumber offset versus wavelength); (e), (f) group velocity relative to velocity away from Bragg resonance. Solid and dotted curves correspond to eigenmodes formed by counterpropagating (c), (e) even–even and odd–odd or (d), (f) even–odd and odd–even supermodes of coupled waveguides, respectively. (g), (h) Transmission through the first (solid curve) and second (dashed curve) output ports, with fixed −3.5 dB offset for direct comparison with experimental data.

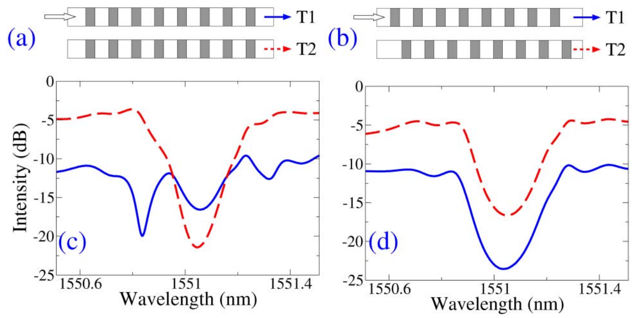

Fig. 3. (Color online) Experimental results. Coupler geometry: (a) symmetric and (b) antisymmetric. Measured transmission spectra from the first (solid) and the second (dashed) waveguides of (c) symmetric and (d) antisymmetric coupler when the light is coupled to the first waveguide.

varies when the wavelength is tuned across the Bragg resonance.

In a sharp contrast to the symmetric coupler, for the coupler with antisymmetric grating alignment, the ratio between the output intensities at the first and second waveguides remains constant for all wavelengths including the region of strong Bragg reflection, seen as an almost constant offset between the transmission curves shown in logarithmic (decibel) scale in Figs. 2(h) and 3(d). This happens because the two eigenmodes in an antisymmetric structure are composed of counterpropagating even–odd or odd–even modes, and due to this symmetry, the Bragg gaps for both eigenmodes fully coincide. This is consistent with earlier studies demonstrating that a single Bragg resonance for all supermodes can be achieved with coupled shifted gratings [11,12,14,15] or with a tilted grating [9,10]. Such spectral properties are especially advantageous for realizing add–drop multiplexors, whereas undesirable additional reflection peaks would generally occur for couplers with a single waveguide grating [8] or unshifted gratings [13]. We note also that the intermode dispersion is absent for the antisymmetric coupler as the dispersion curves are the same up to a constant offset of propagation constants [Fig. 2(d)]. In particular the group velocities of both supermodes are reduced simultaneously as the wavelength is tuned close to the Bragg gap edge [Fig. 2(f)], which is an attractive feature for nonlinear switching [18,19].

In conclusion, we have fabricated Bragg grating couplers using the femtosecond laser direct-write technique and demonstrated precise control of the phase shift between the individual Bragg gratings. We have shown that, for antisymmetric configuration, the spatial coupling is independent of wavelength, which demonstrates the feasibility of laser-written devices for the spatiotemporal control of slow-light pulses [18,19] whose group velocity can be manipulated in the vicinity of Bragg resonance. We anticipate that the fabrication of such structures in nonlinear and active glasses will offer further opportunities for all-optical control of light, including the potential to simultaneously delay and switch signals between the output ports by varying the optical power [18].

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