Femtosecond direct-write überstructure waveguide Bragg gratings in ZBLAN

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Received July 9, 2012; accepted August 17, 2012;
posted August 21, 2012 (Doc. ID 172230); published September 20, 2012

Strong waveguide Bragg gratings (10.5 dB transmission dip) were fabricated using the femtosecond (fs) laser direct-write technique in ZBLAN glass. The Bragg gratings are based on depressed cladding waveguides and consist of planes, periodic according to the Bragg condition, which are constructed from a transverse hexagonal lattice of smaller point features. Such gratings are a key step toward the realization of mid-infrared monolithic waveguide lasers using the fs laser direct-write technique. © 2012 Optical Society of America

OCIS codes: 230.7370, 230.1480, 350.3390.

Mid-infrared lasers are of growing interest because the spectral region coincides with the characteristic vibrational–rotational absorption lines of the vast majority of gaseous molecules, but also contains two atmospheric transmission bands and, therefore, features many applications, such as spectroscopy, LIDAR, and free-space optical communication. These applications benefit from the availability of a cheap, compact, and robust laser source with excellent beam quality and narrow linewidth.

We recently demonstrated efficient Tm:ZBLAN and Ho, Tm:ZBLAN waveguide lasers emitting around 2 μm [1,2]. The devices are based on mirrors, butt-coupled to low propagation loss femtosecond (fs) laser-written depressed cladding waveguides (WGs). However, for a robust laser it is desirable to integrate Bragg gratings into the waveguide in the form of distributed feedback (DFB) or distributed Bragg reflector (DBR) structures, thereby resulting in a monolithic device with narrow linewidth output. In this Letter, we demonstrate the first step toward the realization of such a device, the design and fabrication of depressed cladding waveguide Bragg gratings (DCWBGs).

DFB structures have been demonstrated in phosphate glasses, which respond with a positive index change upon fs laser irradiation [3]. Fabricating similar structures in fluoride glass, such as ZBLAN, which responds with a negative index change and thus requires a depressed cladding WG, is a major challenge. The guided mode of a depressed cladding WG is predominately confined to unmodified glass; however, the coupling strength of a Bragg grating into the counterpropagating mode relies on the overlap of the grating modifications with the guided mode and their refractive index contrast [4]. Therefore, modifying the core of the depressed cladding WG is required to obtain the necessary mode overlap, but placing periodic negative index modifications inside the core of a depressed cladding WG reduces the index contrast between the core and surrounding cladding and thereby increases the confinement loss (CL). Furthermore, the grating transverse dimensions need to be large due to the large core diameters (>15 μm) involved, arising from the limited index contrast of the ZBLAN WGs ($\Delta n_{\mathrm{clad}} \approx 77 - 1.6 \times 10^{-3}$).

Single axial point-by-point grating structures within the core of an optical fiber have been demonstrated [5], but they tend to suffer from either a weak coupling strength associated with a small mode overlap or large scattering losses associated with small or large diameter voids. These structures are undesirable since they either do not provide enough feedback for laser operation or the scattering losses negatively influence the performance of a DFB laser. In this Letter, we show that strong gratings, similar in structure to conventional gratings comprising planes of index change, can be inscribed into ZBLAN using fs laser direct-write methods.

The waveguide Bragg gratings (WBGs) consist of planes, periodic according to the Bragg condition, which are constructed from a transverse hexagonal lattice of smaller point features (Fig. 1). Each modification of

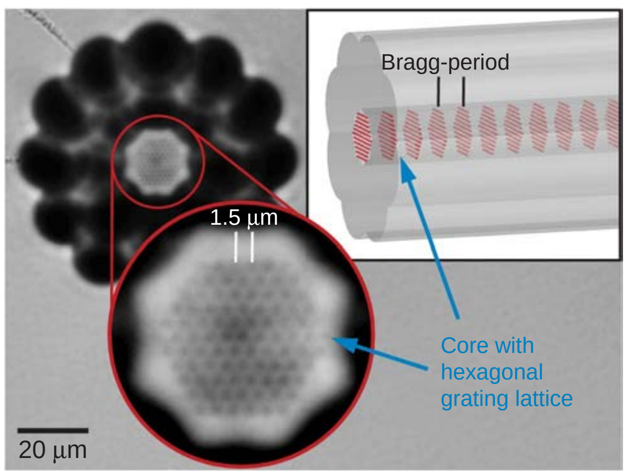

Fig. 1. (Color online) End on, brightfield microscope image of the WBG revealing the hexagonal lattice of point features within the core of the waveguide. The inset shows a three-dimensional rendering of the structure (not to scale).

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the hexagonal lattice is inscribed by on/off modulating the laser according to the Bragg condition while translating it along the WG axis. The phase between each point feature within a plane is maintained by locking it to the encoder position feedback of the translation stages, as recently demonstrated by Brown *et al.* [6].

The DCWBGs were inscribed 300 μm below the surface with an ultrafast Ti:sapphire oscillator (emtolasers FEMTOSOURCE XL 500, 800 nm, 5.1 MHz, 550 nJ, <50 fs). The laser output was focused with a 100 × 1.25 NA oil immersion objective, with the back aperture completely filled, to inscribe the bottom half of the depressed cladding in the cumulative heating regime [7] at 100 nJ pulse energy and 16.6 mm/s feedrate. The strong heat diffusion in the cumulative heating regime inhibits the fabrication of micrometer- or submicrometer-size structures, which are required for low-order Bragg gratings. Thus the laser repetition rate was reduced with an external electro-optic pulse picker to 100 kHz for inscribing the grating from bottom to top. The 100 kHz pulse train was 50% duty cycle on/off-modulated and synchronized to the position feedback provided by the 2 nm resolution encoders of the translation stages (Aerotech). Ten laser pulses were incident on the glass per Bragg period (1040 nm) at a translation speed of 5.2 mm/s to form the second-order grating at 1550 nm. After the grating fabrication the repetition rate was changed back to 5.1 MHz for inscribing the top part of the cladding. The WBG is based on a 15 μm core depressed cladding WG to provide single-mode guiding at 1550 nm. A 33 μm wide cladding is placed around the core, constructed from two rings, the first with eight and the second with 12 modifications of 20 μm diameter each. The grating cross section consists of a seven-ring, 1.5 μm pitch hexagonal lattice (169 points) with a total width of 21 μm, extending across the entire core and partially into the cladding. However, the inscription of the upper cladding part after the grating results in partial erasure of the hexagonal lattice (Fig. 2). Furthermore, less grating contrast is observed in close proximity to the cladding, which is likely caused by thermal annealing as the fs laser heats the material during cladding inscription. This is avoidable by inscribing the grating after the waveguide cladding. Even though the structure is highly complex, the total fabrication time for a 5.8 mm long DCWBG is less than 10 min.

Figure 3 shows the transmission and reflection spectrum of a 5.8 mm long second-order grating at 1550 nm inscribed with 40 nJ pulse energy. The grating features a single transmission dip of 10.5 dB ($\kappa L = 1.88$) and has a 3 dB bandwidth of 230 pm. No evidence of birefringence is present in the spectra despite the slightly asymmetric grating cross section resulting from the annealing. A ≈1 dB transmission loss is apparent on the short wavelength side due to coupling into the continuum of radiation modes [4]. It was also observed that thermal drift in the translation stages can cause the grating planes to exhibit a tilt with respect to the waveguide axis, thus increasing the radiation mode losses.

The reduction of WG index contrast due to the grating requires a careful compromise between the number of modifications, thus grating strength and the resulting increase in CL. Modeling was performed using a commercial finite element analysis software (FEM) package (COMSOL Multiphysics) to investigate the grating strength, CL and mode-field diameter (MFD) with respect to the core fill factor (ratio between the total grating and unperturbed WG core cross-sectional areas). Figures 4(a) and 4(b) show the refractive index profile for a 1.5 μm pitch DCWBG with the corresponding guided mode intensity. Each feature of the hexagonal lattice was approximated by a cylinder with a step-index profile. A single line inscribed at 40 nJ was measured to have a roughly Gaussian index profile with 700 nm FWHM, which under conservation of the cross-sectional area equates to a 750 nm wide step with equal peak index contrast. The modification's small size omitted the accurate measurement of the induced refractive index change with a refracted near-field profiler. Therefore larger structures were inscribed at similar peak intensities with a 1 kHz laser system (described in [8]) and probed for their refractive index contrast, resulting in $\Delta n = -2.5 \times 10^{-3}$. The axial grating profile was approximated by a square wave with 1040 nm period and a duty cycle of 750 nm/1070 nm = 0.72. This results in an average refractive index contrast for each 750 nm diameter cylinder in

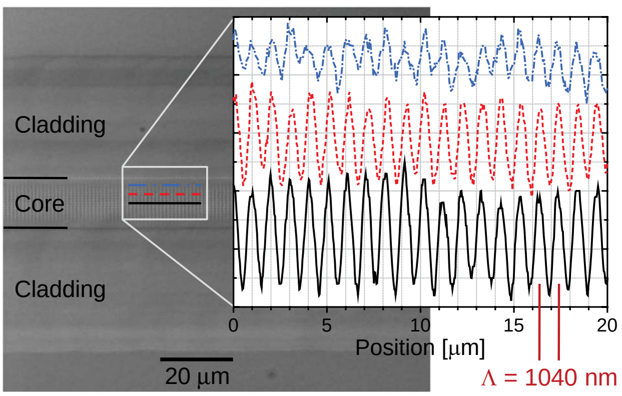

Fig. 2. (Color online) Top-down differential interference contrast image of the WBG with line profiles of the grating at three different positions showing the grating phase relation across the core. A reduction of grating contrast is apparent in close proximity to the cladding (top profile).

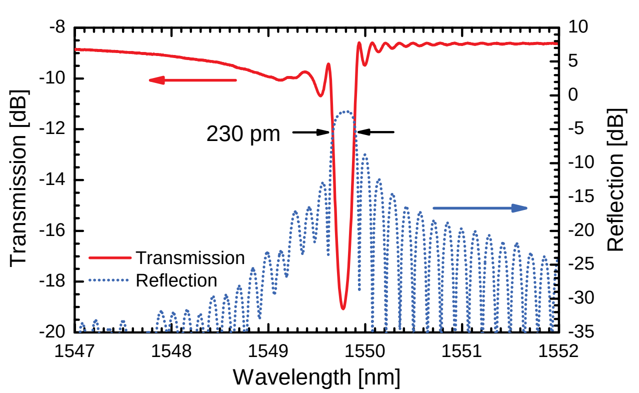

Fig. 3. (Color online) Transmission and reflection spectrum of a 5.8 mm long DCWBG showing a 10.5 dB transmission dip and a 230 pm (3 dB) wide reflection peak with a coupling constant $\kappa L = 1.88$.

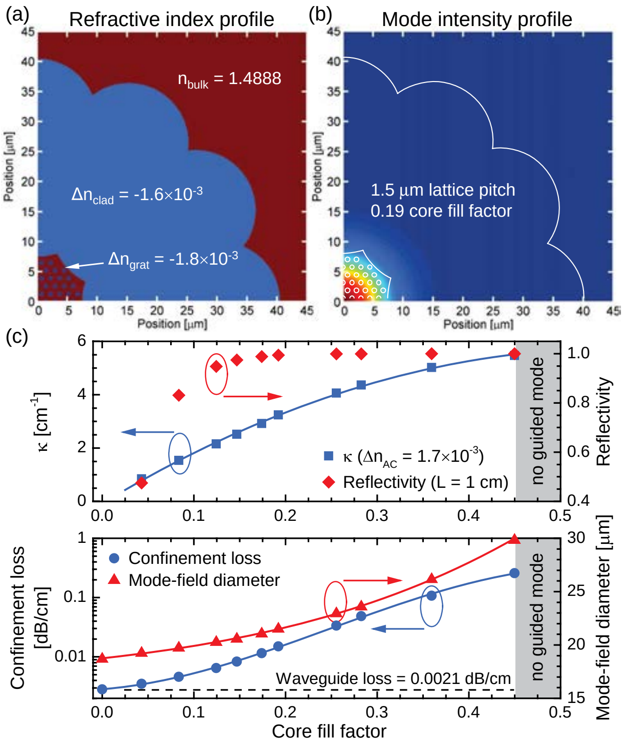

Fig. 4. (Color online) (a) Example of a refractive index profile with 1.5 µm pitch grating (0.19 core fill factor) used for modeling. (b) Corresponding guided mode intensity profile. (c) Coupling constant κ, grating reflectivity, CL and MFDs of the guided mode versus the fill factor. The solid lines are a guide for the eye only.

the hexagonal lattice of $\Delta n_{\text{grat}} = -2.5 \cdot 10^{-3} \times 0.72 = -1.8 \times 10^{-3}$. The grating coupling constant was calculated from [4]

$$\kappa_{\text{AC}} = \frac{4\pi}{\lambda} c_2 \frac{\iint \Delta n_{\text{AC}} E E^* \mathrm{d}x \mathrm{d}y}{\int E E^* \mathrm{d}x \mathrm{d}y},$$

where $c_2 = 0.156$ is the second-order Fourier coefficient of a 72% duty cycle square wave. By comparing the simulation with the experimental results, an AC refractive index contrast $\Delta n_{\text{AC}} = 1.7 \times 10^{-3}$ was found for the 10.5 dB strong grating. In comparison, phase mask inscribed first-order gratings at 1550 nm in ZBLAN fibers using a fs laser exhibit a $\Delta n_{\text{AC}} = 0.86 \times 10^{-3}$ [9].

For low fill factors, only a minor increase in CL and MFD from the unperturbed WG is observed. However, the grating strength is weak. A strong reflection (>90%) occurs for fill factors larger than 0.125 (1.9 µm hex pitch). According to the modeling, a core fill factor around 0.2 (1.5 µm hex pitch, like the inscribed DCWBGs) is a good compromise between the grating strength (99% reflector) and CL. The ≈0.015 dB/cm CL is about a tenth of the lowest loss fs direct-write depressed cladding WGs [10] and also the MFD increases by only 15%. The maximum fill factor that will still support a guided mode is 0.45 (1.0 µm pitch). Even though the grating is a 99.98% reflector, the CL is two orders of magnitude larger compared to the unperturbed waveguide and the MFD increases by more than 50%.

To the best of our knowledge, we have demonstrated, for the first time, that it is possible to construct Bragg-grating structures from a lattice of point features within the core of a depressed cladding WG. The freedom in waveguide shape of the depressed cladding architecture combined with the full spatial control over the grating cross section opens up new avenues, such as the fabrication of mode conversion based on antisymmetric gratings [11], mode selective gratings [12], and monolithic DFB waveguide lasers.

This work was produced with the assistance of the Australian Research Council (ARC) under the Centres of Excellence and Linkage Infrastructure, Equipment and Facilities programs. S. Gross acknowledges the support of the iMQRES scholarship.

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Volume Ends:	Jan - Dec
Document Type:	Journal; Academic/Scholarly
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Abstracted / Indexed:	Yes
Media:	Print
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