High Reflectivity (98%) and Narrowband (<1nm) Gratings Fabricated in a Novel Multimode Fibre

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ABSTRACT

We report what is, to our knowledge, the first demonstration of strong Bragg reflection gratings operating at ~1550 nm written using standard phase mask techniques in a novel multimode fiber. A reflectivity of > 98% and a bandwidth of < 0.5 nm in very good agreement with modeling predictions have been observed.

Keywords: Fiber Bragg grating, multimode fiber, optical communication, biomedical spectroscopy

1.INTRODUCTION

Bragg gratings in single mode fiber have been used commercially in optical fiber communications networks and fiber sensor systems. However, Bragg gratings in multimode fibers have been received attention to a lesser extent. In 1994, K. H. Wanser *et al* [1] first calculated the theoretical spectrum of multimode fiber Bragg gratings (MMFGs) and suggested their use for micro-bend sensing. A grating was fabricated in a graded index (GRIN) fiber that had a reflection spectrum of 15nm wide centered at 1560nm, contained multiple peaks, and had a minimum transmission of 3.4% with selective mode launching. This group later reported a detailed analysis of MMFGs behavior [2], including temperature and polarization characteristics. Multimode fibers have the advantage of simple coupling to and light collection from lasers. In particular, multimode fibers with Bragg gratings are potentially a key element for biomedical spectroscopic sensing. However, the wideband and low-reflectivity characteristic of multimode fiber gratings are fundamental limitations for use in biomedical applications and optical networking. A breakthrough did not occur until the proposal of a novel multimode fiber structure consisting of alternating high and low refractive index shells tailored for improving Bragg grating performance [3].

In this letter, we report the first fabrication of strong reflection gratings successfully written into the novel multimode fiber with a phase mask illuminated by 248nm KrF excimer laser radiation. The peak reflectivity (98%) and 3dB bandwidth (1nm) of the novel multimode fiber Bragg gratings have been observed at a center wavelength of approximately 1555nm. We have realized the goal of enabling narrow-band, high reflectivity gratings in the novel multimode fiber structure proposed. We believe that multimode fiber Bragg gratings will influence the development of Raman spectroscopy systems for biomedical applications, and will also provide another option to the local area optical network designer.

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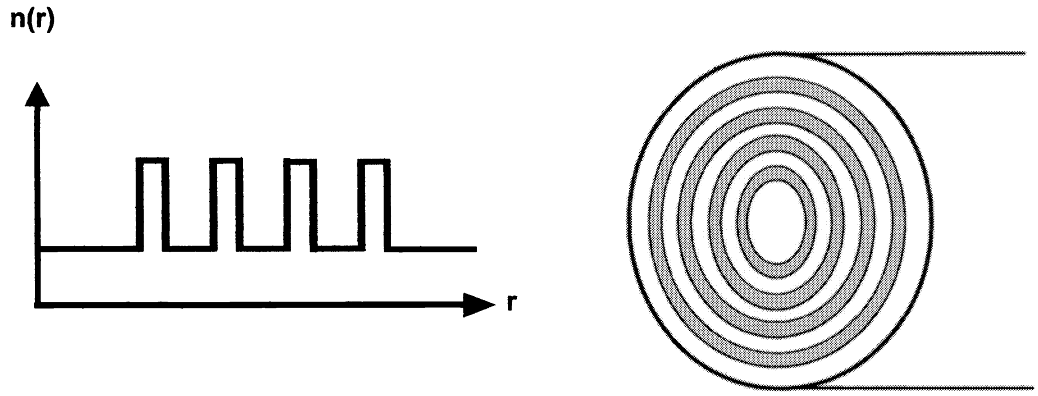
2. NOVEL MULTIMODE FIBER

For a standard multimode fiber, each of the modes in the fiber travels with a slightly different propagation constant, or effective index, and resonates with the gratings at a different wavelength. It is impossible to attain the narrowness of the response due to the different propagation constants. At the same time, the spread in effective indexes will lead to a low reflectivity response. In order to facilitate the fabrication of the high reflectivity and narrowness band Bragg gratings in multimode fiber, we proposed a novel multimode fiber structure [3] which consists of alternating cylindrical shells of higher and lower refractive index, shown as Fig 1.



(a) (b)

Fig.1. (a) Refractive index profile. (b) Fiber side view. Shaded regions represent areas of higher refractive index and unshaded regions represent uniform cladding regions with lower refractive index.

This structure is intended to minimize the difference in propagation constants of the various guided modes. To develop an intuitive conception of an MMF that will minimize the difference in propagation constants, we consider an analogy between the propagation of an electromagnetic mode within a fiber and a bound quantum mechanical particle in a potential well. In the scalar approximation for the electromagnetic mode field, the fiber problem can be described by the similar Schrödinger equation used for a bound particle:

$$[\nabla_T^2 + k_0^2(n^2(r) - n_{eff}^2)]\Psi(r) = 0 \qquad (1)$$

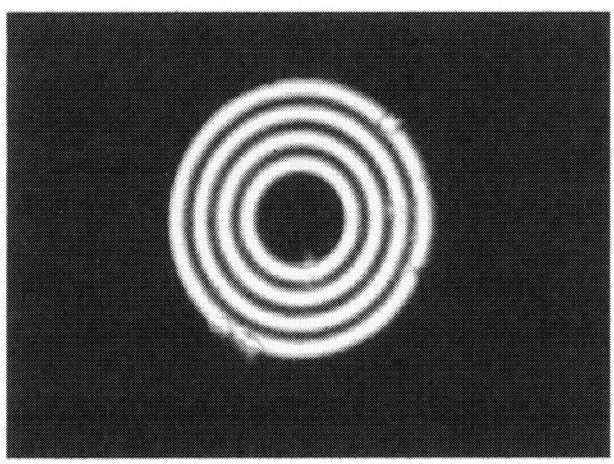
where ∇_T is the del operator for transverse spatial coordinates, r is the radial position coordinate, k_0 is the vacuum wave vector, $n(r)$ is the radial index profile, n_{eff} is the effective index, and $\Psi(r)$ is the scalar field.

The energy eigenvalues of a bound particle are analogous to the effective indices of the modes in the fiber. If a quantum well is made sufficiently shallow, it will contain one energy level, which can be analogous to a single mode fiber. The situation of interest is that of closely spaced potential wells. As the well are brought closer together, the energy level splitting increases. The analogous result also implies that a fiber with periodically varying radial index profile as shown in Fig.1 should have many modes with very closely spaced effective index or propagation constants, which would enable a narrowband reflection response while still supporting multiple modes. By minimizing the difference in propagation constants, all modes in this novel multimode fiber will interact with Bragg gratings in roughly the same way. This allows a reflection response in the novel multimode fiber that is very similar to that in a standard single mode fiber. The close spacing in the effective indexes for different modes is exactly what is needed for the design of narrow-band MMFGs.

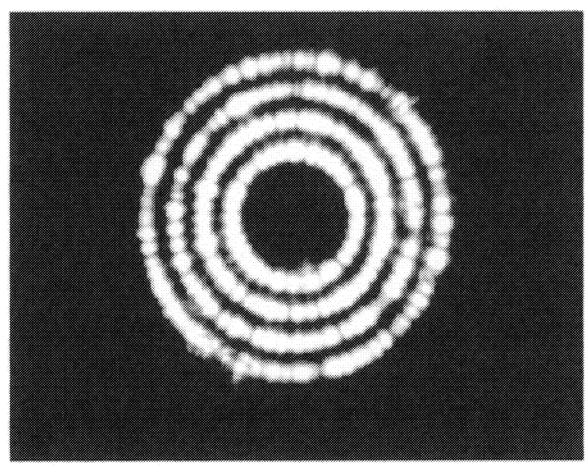
In the special case in which the thickness of the cylindrical shell (parts of higher reflective index) is small compared to its mean radius, the shell approximates a planar structure. Thus, the condition for single-mode (ignoring polarization for the moment) operation in each isolated cylindrical shell can be appreciated using simple planar waveguide analysis.

3. EXPERIMENTAL RESULTS

A fibre perform was made with four higher-refractive-index shells and made into fibre with optimized dimensions based on our simulation results [3]. These dimensions (first shell radius 25λ; shell thickness 4λ; and shell spacing 10λ) were shown to provide excellent Bragg grating performance when circularly-symmetric light is coupled into the fibre. The refractive index of shell and cladding is 1.4501 and 1.4446 respectively. The increased index in the shells of the fibre was created by GeO_2 doping. This dopant also increases the sensitivity of the fused quartz to the UV light used for writing the Bragg gratings, and thus we expect gratings to be written primarily into the high-index shells. Initial tests of the special fibres were made by coupling light into the fibre and analysing the output with a video camera. The coupling of light into the novel fibre was tested by observing the transmitted light through a 1.63 m segment of fibre at the exit face. When the entire entrance face was uniformly illuminated, the transmitted light was observed to be tightly confined in the high-index shell regions. For broad-band "white light" excitation, the output rings had no visible structure, while for narrow-band (He-Ne laser or Er fibre amplifier ASE) excitation, some angular intensity variations were observed. In all cases the output light was observed to maintain the polarization of the input, shown in Fig.2.



(a)



(b)

Fig 2. Image of the end face of novel multimode fiber is taken by CCD camera and excited under different light sources. (a) broad-band "white light" excitation; (b) narrow-band excitation.

We wrote Bragg gratings in these fibres using standard phase mask techniques. The fibres were pre-soaked with H_2 gas at 1900 psi for 30 days at room temperature to increase the UV photosensitivity. We wrote the gratings using a 2.5-cm long uniform phase mask designed for writing gratings at 1550 nm with nulled zeroth-order diffraction peak. . The fibre was exposed to 248nm pulses with an energy of 18 mJ for a total duration of 13 min using a KrF excimer laser operating at a repetition rate of 40 Hz. The gratings in the multimode fibre were interrogated with an Er-fibre amplified spontaneous emission (ASE) light source. An optical spectrum analyzer (Ando AQ 6317B) was used to measure the spectrum of the light transmitted through the fiber gratings. The deepest transmission nulls were obtained with the smallest diameter fiber (32 μm inner-shell diameter, 128 μm cladding diameter). High reflectivity Bragg fiber gratings centered at 1554 nm were written in the novel multimode fiber as evidenced by the spectra shown in Figure 3. The transmission loss at the 1554-nm center wavelength is greater than 16 dB. This corresponds to a grating reflectivity of approximately 98%. The bandwidth of the grating response is < 0.5 nm at the 3 dB point.

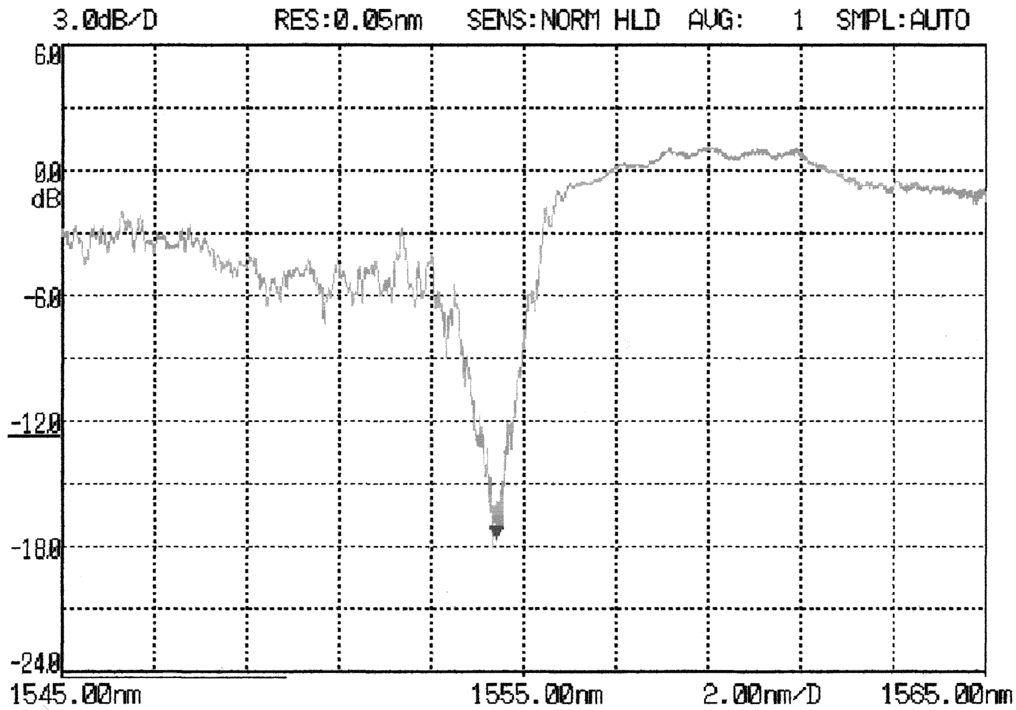


Fig.3. Transmission spectrum of a Bragg grating written in the novel multimode fiber by the use of a uniform phase mask and measured using an Er fiber ASE light source.

4. DISCUSSION

In a previous publication [3] we presented a theoretical simulation of Bragg grating performance in this novel multimode fiber, shown in Fig.4. Under conditions where only modes of circular symmetry are excited, we can expect to be able to achieve peak reflectivities of 100% with full-width at half-maximum (FWHM) bandwidth of $2.5\times10^{-4}\,\lambda$ which is ~ 0.4 nm for a Bragg grating wavelength of 1554 nm. In this regime, the bandwidth is determined by the intrinsic width of the grating resonance associated with each nearly degenerate fiber mode excited. In our experiments, we observed a transmission dip corresponding to a reflectivity of ~ 98% with a 3 dB bandwidth of < 0.5 nm. The conditions for our experiments were somewhat different from those assumed in the theoretical simulations, but we believe that the close agreement with the simulations indicates that the multimode fiber grating is basically performing as expected.

We used the same phase mask to write gratings in a single-mode fiber (Corning SMF-28) for which the fiber parameters are well characterized. The effective index for the modes excited the novel multimode fiber can be calculated from a comparison of the wavelength of the grating resonance in the SMF-28 fiber with the wavelength for the grating resonance in a large-diameter novel multimode fiber for which the conditions of our modeling analysis in [3] apply at λ = 1554 nm (first shell radius 25λ; shell thickness 4λ; and shell spacing 10λ). We find that the effective index corresponds to a normalized propagation constant b = 0.64, in very good agreement with the calculated constant b for the low-order near-degenerate modes.

The spectra in Figure 3 show a significant (~ 2 dB) loss on the short wavelength side of the Bragg resonance. This is somewhat larger than the ~ 1 dB radiation loss usually seen with single mode fiber gratings [4]. We speculate this larger radiation loss is due to the asymmetric nature of the Bragg grating written with lateral UV exposure. The substantial path difference between one side of the outer shell and the other results in a blazed grating being written, and one would expect the asymmetry to cause mode mixing and thus produce a broad reflection pedestal, shown as Fig.5. A symmetrical exposure technique would be likely improve the grating performance, and permit larger-diameter fibers to be used.

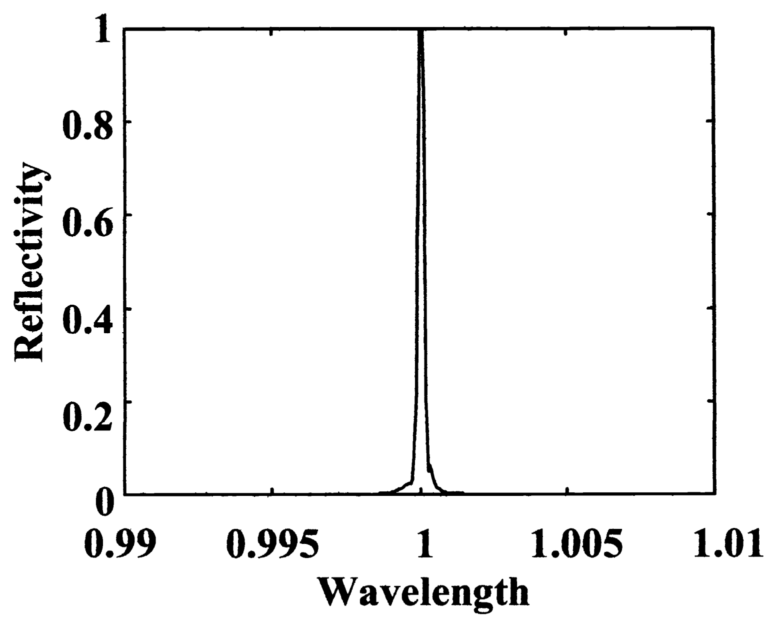


Fig.4. Grating response of proposed fiber with p=1 modes excited

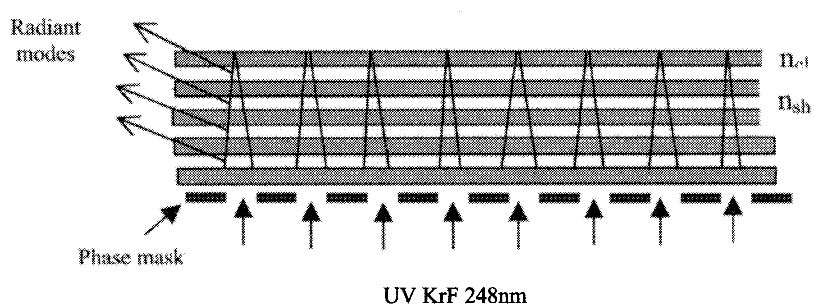


Fig.4. Schematic of a larger short-wavelength loss in the ring fiber Bragg gratings

5. CONCLUSION

We have successfully realized the goal of enabling narrow-band high-reflectivity gratings to be written in a novel multimode fibre structure consisting of alternating high and low refractive index shells. We believe that multimode fibre Bragg gratings will provide another option to the local area network designer, and also influence the development of fibre optic probes in biomedical applications.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

[1] K. H. Wanser, K. F. Voss, and A. D. Kersey, " Novel fiber devices and sensors based on multimode fiber Bragg gratings," Proc. SPIE, vol 2360, 256-268, (1994)

[2] T. Mizunami, S. Gupta, T. Yamao, and T. Shimomura, "Multimode fiber Bragg gratings – spectral characteristic and applications," Int. Conf. Integrated Optics Optical Fiber Commun./Eur. Conf. Optical Commun., vol 3, 182-185, (1997)

[3] T. Szkopek, V. Pasupathy, J. E. Sipe, and P. W. E. Smith, "Novel Multimode Fiber for Narrow-band Bragg Gratings" IEEE J. Selected Topics in Quantum Electron. vol.7, 425-433, (2001)

[4] V. Mizrahi and J. E. Sipe, "Optical properties of photosensitive fiber phase gratings," J. Lightwave. Technol. vol 11, 1513-1517 (1993)