with twofold larger accumulated fluence (33 kJ/cm²). The resulting gratings are highly stable after F₂-laser trimming owing to prior removal of the residual hydrogen during the baking step.

![Graph of peak grating reflection versus wavelength shift](image)

**Fig. 2** Peak grating reflection and resonance wavelength shift against 157 nm post exposure fluence for weak grating shown in Fig. 1 inset

The F₂-laser trimming process described here is fundamentally different and offers considerable process control, especially in comparison with the 193 nm and 248 nm post-writing results by Dyer et al. [2], who noted no measurable enhancement for 248 nm exposures while 193 nm exposure only offered abrupt enhancement in single pulse exposures above a high pulse fluence threshold of > 500 mJ/cm². Furthermore, Ge-doped fibres were tested at these longer wavelengths, which suggests that much weaker processes are anticipated for the hydrogen-free telecommunication fibres as tested with the present 157 nm laser. In contrast, the results in Fig. 2 were accumulated over ~10⁷ pulses which makes possible the precise post-F₂-laser trimming of grating strength to ±0.1 dB accuracy or grating wavelength resonance tuning to ±1 pm.

![Graph of resonant wavelength shift versus fluence](image)

**Fig. 3** Resonant wavelength shift for 1 cm FBGs against 157 nm laser exposure at single pulse fluence of 3.8 mJ/cm² and 22 mJ/cm².

Seed gratings had reflectivity of 2.6 dB and 1.7 dB, respectively.
- 3.8 mJ/cm²
- 22 mJ/cm²

The practical range for wavelength tuning and reflection amplification available in F₂-laser trimming of FBGs depends both on the initial strength of the KrF-laser-formed grating and on the single pulse fluence of the F₂ laser. Fig. 3 compares the wavelength shift for 2.4 and 1.7 dB 1 cm pre-formed gratings as a function of accumulated 157 nm fluence when using 3.8 and 22 mJ/cm² fluence-per-pulse, respectively. The stronger per-pulse fluence yielded a weaker amplification to 7.5 dB reflection compared with 14.3 dB reflection, and a smaller wavelength trimming range of 1 nm compared with 1.33 nm. F₂-laser damage of the fibre is suspected with larger single pulse exposure. Furthermore, the reflection amplification is less apparent in strong seed gratings; only a ~3 dB enhancement was observed for a pre-formed 20 dB FBG of 1 cm length.

The uniform post F₂-laser exposure of an FBG presents a novel AC index change above a strong fundamental DC index response in the fibre. Although the exact photosensitivity mechanism is not clear, the strong DC response is associated with the 7.9 eV photon energy which bridges the germanosilicate bandgap (7.1 eV for 5% doping) [6] and can directly interact with the Ge-O bond to support a single-photon process. Such strong interaction localises the VUV-induced index change within several microns of the cladding-core interface. prolonged low-fluence (< 10 mJ/cm²) exposure was shown to reduce the penetration depth by an unknown incubation process [4] and eventually damage the waveguide. Such mechanisms are likely to be related to the saturated index change (Fig. 2) and weaker response at higher fluence (Fig. 3).

The fundamental mechanism for the AC response is very different than the Type II (damage) response inferred in [2] for 193 nm post-laser trimming. In contrast to their high fluence (> 500 mJ/cm²) and single pulse exposure, the ~10⁷ pulses of ~4 mJ/cm² exposure at 157 nm wavelength describe a more gentle and controlled process consistent with a Type I mechanism. This AC response is likely associated with defect states locked in by the 248 nm laser in hydrogen-loaded fibre. As evidence, the F₂ laser excited a blue-fluorescence only in regions of the fibre pre-exposed with the 248 nm laser.

Low loss mode converter based on adiabatically tapered hollow optical fibre

S. Choi, K. Oh, W. Shin and U.C. Ryu

A new mode converter based on tapered hollow optical fibre is proposed and experimentally demonstrated. Two segments of a singlemode fibre and a tapered hollow ring-core fibre were concatenated serially to convert a fundamental mode to a ring-shaped mode. The fabrication, far field pattern and insertion loss of the proposed mode converter were measured and discussed.
Introduction: A functional device that can convert the fundamental mode of a conventional single-mode optical fibre to one of higher-order modes of a multimode optical fibre, and vice versa, could have important potential in optical sensing and communication. To utilise mode field extended to the cladding and high dispersion of the higher-order modes, all-fibre mode converters based on the periodic coupling have been demonstrated [1 - 3]. These devices, however, are highly dependent on temperature and strain owing to the periodic nature of structures.

In addition to previously reported applications, mode converters could be applied to high-speed local area networks (LANs). To achieve the high-speed multimode fibre (MMF) links such as Gigabit Ethernet, it is necessary to reduce the differential modal dispersion of MMFs. Since the mode from a singlemode fibre (SMF) pig-tailed to a laser diode under-fills the MMF core, the diameter of which ranges from 50 to 62.5 µm, the launching condition is critical to reduce the modal dispersion; furthermore, when an MMF has a central dip in the refractive index profile, central launching the output from SMF to MMF will induce a significant amount of differential modal delay (DMD) resulting in severe reduction in transmission capacity. To improve bandwidth and to reduce DMD in MMFs, an offset launching technique, and vertical cavity surface emitting lasers (VCSELs) with a ring-shaped output mode, have been proposed to improve bandwidth [4, 5].

In this Letter, we report, for the first time to the best knowledge of the authors, a new type of mode converter that efficiently converts the fundamental mode of a singlemode fibre to a ring-shaped symmetric mode using an adiabatically tapered hollow optical fibre (HOF) segment. The evaluation of the insertion loss for mode converters according to the various HOFs and the taper conditions is explored. Previous research on HOFs has been limited to the delivery of high-power infrared lasers, e.g. Er:YAG and CO₂ [6]. We expand HOF applications to the fibre optic communication window in the wavelength of 1.31 and 1.55 µm, demonstrating all-fibre mode converters.

Device design and analysis: Fig. 1a is a schematic diagram of the structure of the proposed mode converter. Two segments of a conventional SMF and a tapered HOF with a ring core were concatenated serially to convert the fundamental mode to a ring-shaped mode. The ring mode is then launched to an MMF for further applications. Note that the middle HOF has a ring core, which is tapered to reduce coupling loss with the SMF exciting only the fundamental mode into HOF. In the MMF side, the HOF was designed to avoid the central refractive index dip of the MMF reducing the DMD. The micrograph of an actual mode converter and the launching scheme into the MMF are shown in Figs. 1b and c, respectively.

The range of the optimum hole radius of the HOF to avoid a central dip of the MMF was obtained by numerical mode analysis. The HOF design parameters, i.e. width, the location, the index differences of the ring core, were optimised for efficient mode conversion. Relative index difference Δ between the ring core and silica cladding was <0.34% and the width of the ring was adjusted to maintain the fundamental mode at 1.31 µm when an HOF is tapered down to a solid fibre waveguide as shown in Fig. 1a. As the hole radius increases, the fundamental mode guided in the HOF expands rapidly to the cladding, resulting in a poor coupling efficiency to the MMFs. In contrast, if the hole radius decreases, significant overlap with the central dip in the MMF develops. Considering these trade-offs, the range of hole radius from 3.4 to 6.0 µm was obtained.

Experiments and results: The performances of the HOFs were fabricated by modified chemical vapour deposition (MCVD) process. The core layer was deposited inside the substrate tube by doping germanium with SiO₂ to increase the refractive index. The substrate tube was then collapsed, maintaining the central hole with a certain diameter. Elaborate controls over temperature and drawing tension were performed in the fibre drawing process to keep the hole intact in the axial direction. The HOF preform with the outer diameter of ~16 mm was drawn to the fibre with the outer diameter of ~125 µm. The fibre drawing furnace temperature was maintained at 1980°C for the draw speed of 6 to 8 m/min. The cross-section area of a HOF taken with a microscope is shown in Fig. 2a. The bright ring-shaped region represents the germanium-doped ring core.

The HOFs with hole diameters of 4 to 12 µm, outer diameter of ~125 µm, and length of 100 to 150 mm, were used to fabricate the proposed mode converter. To taper down the HOF for mating the SMF end, two tapering methods were employed. One was to apply an electric arc locally on the HOF to produce a short and abrupt taper. The other was to taper adiabatically the HOF, simultaneously heating with a micro torch and pulling in a fused fibre coupler station to form a longer taper. One end of the HOF was tapered to a solid fibre waveguide and then fusion spliced with an SMF. The SMF end was also tapered down to minimise the insertion loss matching the mode field diameter with that of the tapered HOF end.

To observe the far field pattern of the proposed mode converter, the beam from a He-Ne laser was focused on the SMF end through the objective lens and the field pattern from the HOF end was measured by a charge coupled device (CCD) camera. The output beam pattern of an HOF is shown in Fig. 2b. As expected, the mode showed a clear ring-shaped far field pattern, comparable to symmetric higher-order modes in a cylindrical optical fibre.

Fig. 1 Mode converter based on tapered HOF

a) Schematic diagram of SMF-HOF-MMF structure
b) Micrograph between SMF and HOF

c) Launching scheme into MMF

Fig. 2 Hollow optical fibre with ring core

a) Cross-section area
b) Far field pattern

Fig. 3 Insertion loss against various hole diameters

- device tapered by arc
- device adiabatically tapered by fibre pulling system
- exponential fit
Multi-wavelength, continuous wave fibre Raman ring laser operating at 1.55 \( \mu \)m

C.J.S. de Matos, D.A. Chestnut, P.C. Reeves-Hall, F. Koch and J.R. Taylor

A four-wavelength, continuous wave, fibre Raman ring laser has been demonstrated at room temperature using fibre Bragg gratings as the wavelength-selective elements with applications as a multi-wavelength source for optical fibre telecommunications. Channel spacings were 5 nm between 1551.6 and 1565.1 nm with 14.9 dBm total output power.

Introduction: Multiple wavelength sources are a key component of high capacity optical fibre telecommunication systems. Currently commercial systems employ many distributed feedback (DBF) laser diodes as wavelength division multiplexed (WDM) channel sources, with signals combined using arrays of optical couplers. Recently considerable effort has gone into the development of multi-wavelength fibre laser sources in an attempt to reduce the complexity of WDM systems. Although a dual wavelength DBF fibre laser has been demonstrated [1] the majority of interest has been with erbium-doped fibre ring lasers. To support simultaneous gain at multiple wavelengths in erbium-doped glass, the homogeneously broadened room temperature gain characteristic can be modified. This can only be achieved in erbium by external cooling, such that the gain is predominantly inhomogeneous. This has resulted in many approaches based upon the use of a liquid nitrogen cooled gain fibre at 77 K [2 – 4]. An alternative approach of Q-switching an erbium fibre laser with a scanning Fabry-Perot has been demonstrated but produced pulses at repetition rates of only a few kHz [5]. Continuous wave (CW) multi-wavelength output of an erbium ring laser has also been achieved with the use of an acousto-optic frequency shifter at room temperature but this adds to the complexity of an active component [6].

The inhomogeneously broadened gain of stimulated Raman scattering (SRS) provides an alternative approach to designing a room temperature WDM source. Over 19 WDM channels have been demonstrated previously using a fibre Raman laser with a Fabry-Perot etalon in the cavity but with obvious restrictions on individual tuning of channels [7]. In this Letter a four-wavelength, CW fibre Raman ring laser is described in which fibre Bragg gratings (FBGs) are used as the wavelength-selective elements offering the possibility of specific wavelength selection, tunability and gain-flattened output. Such a source also has potential application as the pump source for Raman fibre amplifiers with a broadened and flattened gain profile that is a result of multiple line pumping.

Fig. 1 Experimental configuration of four-wavelength fibre Raman ring laser

Experiment: The experimental configuration of the four-wavelength fibre Raman ring laser is shown in Fig. 1. The Raman gain medium was 7 km of dispersion compensated fibre (DCF) pumped at 1455 nm by a fibre Raman pump laser providing up to 1.3 W of power, with peak Raman gain at 1555 nm. A counter-propagating pump and signal configuration was used, employing an optical circulator to mix pump and signals, in order to reduce signal noise occurring from high frequency pump oscillations. Four FBGs were coupled into the cavity as the wavelength-selective components using an optical circulator. Reflection wavelengths of the four FBGs were centred at 1551.6, 1556.1, 1560.7 and 1565.1 nm, respectively, with a peak reflectivity of around –2 dB including circulator loss. Each FBG channel had a reflectivity of around –2 dB including circulator loss. Each FBG channel had a reflectivity of around –2 dB including circulator loss. Each FBG channel had a reflectivity of around –2 dB including circulator loss.

References

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S. Choi, K. Oh, W. Shin and U.C. Ryu (Department of Information and Communications, Kwangju Institute of Science and Technology (K-JIST), 1 Oryong-dong, Gwagju, Kwangju 500-712, Korea) E-mail: koh@kjist.ac.kr

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