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# Bismuth-ring-doped fibres

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***Abstract*. A new process for bismuth doping of optical fibres is proposed in which the dopant is introduced into a thin layer surrounding the fibre core. This enables bismuth stabilisation in the silica glass, with no limitations on the core composition. In particular, the $GeO_2$ content of the fibre core in this study is 16 mol %. Spectroscopic characterisation of such fibres and optical gain measurements suggest that the proposed approach has considerable potential for laser applications.**

***Keywords***: *bismuth, optical fibre, fabrication process, FCVD.*

## 1. Introduction

Bismuth-doped silica fibres, developed relatively recently, can be made to lase in the range 1140 to 1550 nm, depending on the core glass composition [1 – 5]. The luminescence spectrum of silica glass singly doped with bismuth extends from 1100 to 1700 nm [6]. Bismuth-doped fibres offer sufficient performance for application in telecommunication amplifiers. The integration of such amplifiers into already existing communication systems would allow the standard C and L bands (1.53 – 1.625 μm) to be considerably extended. Moreover, the silica glass – bismuth system, one of the simplest systems, is of interest for gaining insight into the nature of bismuth-related active centres.

Because of the technical difficulties associated with the strong tendency of bismuth to vaporise [7, 8], there is high current interest in designing various procedures for bismuth doping of fibres. Here, we report a study of a fibre doped with bismuth in a thin layer surrounding the fibre core. Given that ytterbium ring doping has been successfully applied in the fabrication of fibre lasers [9, 10], we used a similar approach to dope fibres with bismuth.

## 2. Preform and fibre fabrication

Fibre preforms were fabricated by the furnace chemical vapour deposition process [11, 12]. To produce a bismuth-doped layer, porous silica glass deposited at 1520 °C was impregnated with an aqueous solution of bismuthyl chloride, BiOCl. The porous layer was then sintered to give a bismuth-doped silica glass layer. Next, a germanosilicate core glass layer was deposited, and the preform was collapsed in a germanium chloride/oxygen atmosphere.

The preforms thus fabricated were similar in refractive index profile but differed in bismuth concentration in the doped layer. The index profile (measured with a York Technology P102 analyser) of the fibre preform doped with about 16 mol % $GeO_2$ is shown in Fig. 1. The preforms were then drawn into fibre. According to estimates from the fibre geometry, the cross section of the bismuth-doped layer had the form of a ring about 600 nm thick (nanolayer) [13].

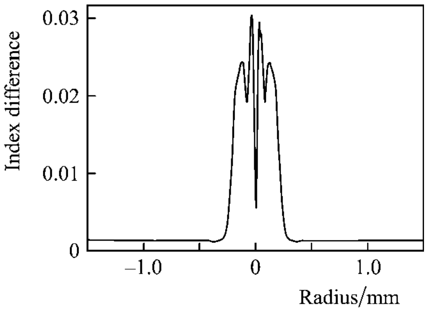

**Figure 1.** Refractive index profile of a bismuth-doped fibre preform.

## 3. Fibre characterisation results

Figure 2 shows the absorption spectra of fibres L, M and H, drawn out from preforms differing in bismuth concentration (low, medium and high). The spectra contain a composite band consisting of three components at 820, 870 and 940 nm. There are also characteristic absorption bands of the OH group at 1240 and 1380 nm. The latter band obscures the absorption band of an active centre. In addition, one can see cutoff regions slightly varying from fibre to fibre (1100 – 1250 nm). The bismuth concentration in fibre L is low, and the characteristic absorption bands are very weak. Fibre M, with a relatively high bismuth concentration and, accordingly, rather prominent characteristic absorption bands, shows the lowest optical loss at 1600 nm: 50 dB $km^{-1}$. In earlier studies, lower passive optical losses in bismuth-doped fibres were achieved ($\sim$ 10 dB $km^{-1}$ [1, 3]), but the present loss level is also acceptable for active fibres.

Figures 3 and 4 show the luminescence spectra of the fibres at excitation wavelengths of 808 and 1350 nm. The

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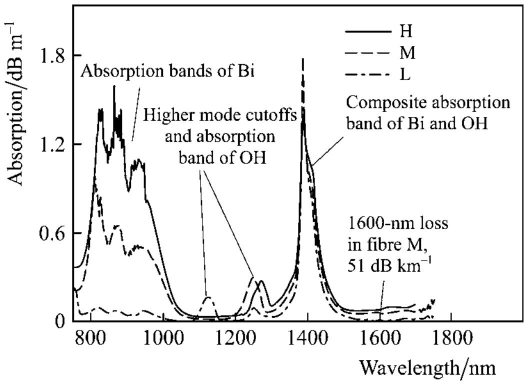

**Figure 2.** Absorption spectra of Bi-ring-doped fibres.

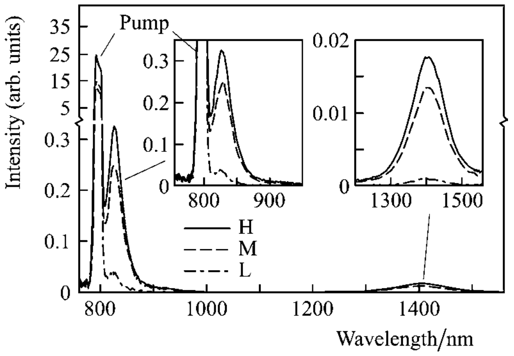

**Figure 3.** Luminescence spectra of the fibres at an excitation wavelength of 808 nm.

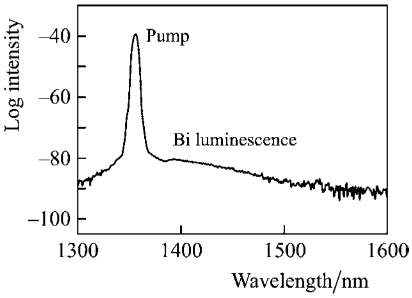

**Figure 4.** Luminescence spectrum of fibre M at an excitation wavelength of 1350 nm.

luminescence intensity is roughly proportional to the absorption in the fibre core. At an excitation wavelength of 808 nm, the spectra show two luminescence bands, near 825 and 1400 nm. Under longer wavelength excitation, there is only one band, centred around 1400 nm.

Note that, in this study, we did not examine bismuth diffusion to the fibre core or germanium diffusion to the bismuth-doped layer. Nevertheless, the luminescence and absorption spectra correlate well with the data reported by Neff et al. [6] for bismuth-doped silica glass.

Figure 5 presents a typical on/off optical gain spectrum, taken with a 20-m-long fibre H pumped at 1350 nm. Optical gain was obtained over the entire spectral range studied, from 1430 to 1530 nm. Raising the pump power from 41 to 292 mW leads to gain saturation, at a level above 9 dB around 1430 nm, with an appreciable gain ($\sim$ 2 dB) at the long-wavelength boundary of the range studied (1530 nm).

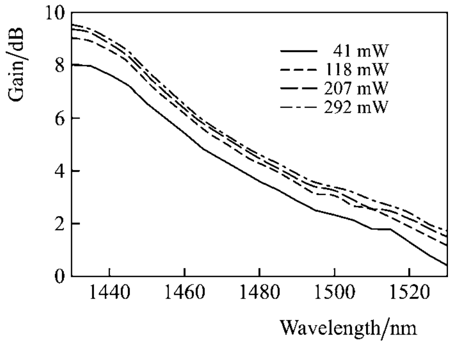

**Figure 5.** Gain spectrum of fibre H pumped at $\lambda_p = 1350$ nm.

Figure 6 shows the spectral dependence of the calculated group velocity dispersion for one of our fibres. The zero dispersion wavelength $\lambda_0$ is near 1850 nm, and the dispersion in the range 1400–1550 nm is normal (in contrast to standard fibres, e.g. Corning SMF-28, which have zero dispersion near 1300 nm). Therefore, utilising this fibre as a gain medium in femtosecond fibre lasers emitting in the range 1430–1530 nm would simplify dispersion compensation in such lasers.

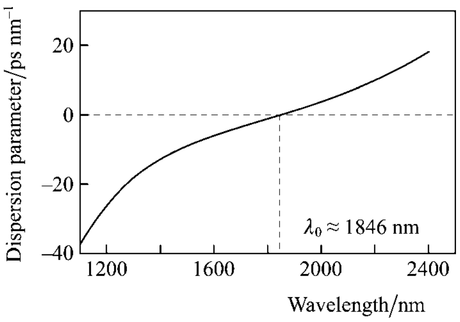

**Figure 6.** Calculated dispersion parameter of the fibre whose index profile is shown in Fig. 1.

## 4. Discussion

Given that the index profile of fibres has a strong effect on their optical parameters, the ring-doped fibre design appears potentially attractive because the thin doped layer in such fibres has little or no effect on their index profile. This approach enables the fabrication of active fibres with tailored waveguiding properties using already known index profiles with no consideration for the effect of the doped layer.

Figure 7 presents examples of conceivable index profiles in fibres containing one active nanolayer [13]. In particular,

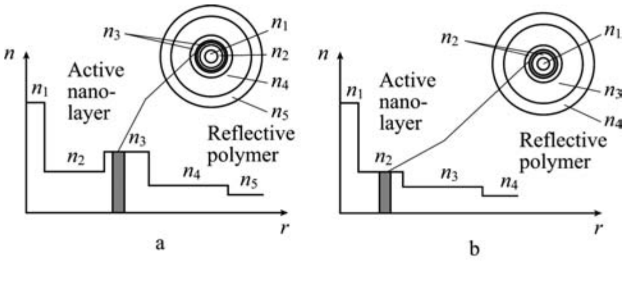

**Figure 7.** Model index profiles in fibres containing one active nanolayer.

the profile in Fig. 7a can be used to produce controlled-dispersion active fibres [14, 15] in which the doped-ring position can be varied controllably.

The index profile in Fig. 7b may ensure enhanced sensitivity to nonlinear effects at a sufficiently large core–cladding index difference ($n_1 - n_3$) [16]. Figure 8 shows a simplified version of this profile, produced in this study. To raise the nonlinearity coefficient [16, 17] by reducing the mode field radius, no increased index region ($n_2$) was produced in the preform. In the model index profile in Fig. 7b, the $n_2$ region is intended to control the fibre mode field radius. Varying the radius, one can control the nonlinearity coefficient of the fibre [17] and the beam intensity in the region of the active ring. Ring doping can be combined with doping of the core with laser-active ions, which will enable fabrication of fibres containing different laser-active dopants in different regions (e.g., in order to avoid interaction between them).

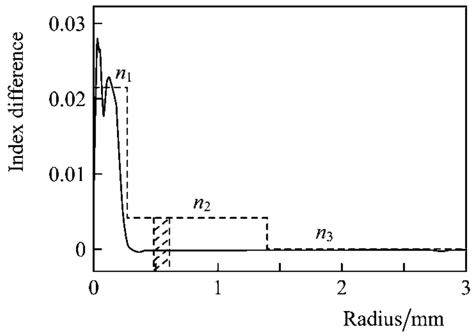

**Figure 8.** Model and actual index profiles in a preform containing an active nanolayer.

## 5. Conclusions

We produced a germanosilicate-core fibre doped with bismuth in a thin layer of its cladding. Owing to the proximity between the core and the bismuth-doped thin layer surrounding it, the loss and luminescence spectra measured upon excitation of the fibre core showed characteristic absorption and luminescence bands of bismuth-related active centres. Optical gain was demonstrated in a wide spectral range (1430–1530 nm), reaching 9 dB at 1430 nm. The passive optical loss level (50 dB km$^{-1}$) is acceptable for active fibres. Thus, the described active-fibre fabrication process has considerable potential for laser and amplifier development.

Optimisation of the proposed doping process will enable the fabrication of fibres with various radial profiles of laser-active ions, which will add flexibility in tuning the optical properties of the fibre.

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