VERY HIGH-REJECTION OPTICAL FIBRE FILTERS

Indexing terms: Optical fibres, Optical filters

An optical filter has been developed using holmium-doped optical fibre. Transmission in the blocking band is $10^{-7}\%$ while transmission in the passband is 85%. The wavelength separation between maximum blocking and maximum pass is only 40 nm.

Introduction: All optical fibre components are essential for miniaturisation of optical systems for communications and aerospace applications. Low-loss fusion-splice techniques enable fibre components to be connected together with minimum insertion losses. Of particular interest are wavelength filters for applications such as wavelength multiplexing. Birefringent optical fibre filters have been reported,[1] but these are hard to reproduce and have a limited rejection. Rare-earth-doped high-grade optical fibres have recently been developed which exhibit very large, sharp absorption bands, while maintaining the low losses of telecommunications fibre in the passbands. This characteristic suggests the construction of compact low-loss wavelength filters with extremely high rejection.

Filter fibre characteristics: Doped fibres with high attenuation have been reported[2] based on a wide range of rare-earth materials. Many rare earths, including Nd^{3+}, have strong fluorescence in the visible or near-infra-red which makes them unsuitable for filter applications in this wavelength region. Fortunately, holmium is known to have no fluorescence between 632 nm and 1100 nm, and this has been confirmed by fabricating a holmium-doped silica fibre. The main fluorescence band of holmium is at a wavelength of $2\,\mu m$, which is outside our range of interest. Note, however, that weak Ho^{3+} fluorescence bands exist in some glasses at 545 nm, 645 nm and 750 nm, but these are not found in silica.

The spectral attenuation of the holmium-doped fibre is shown in Fig. 1. The fibre has a GeO_2/SiO_2 core containing

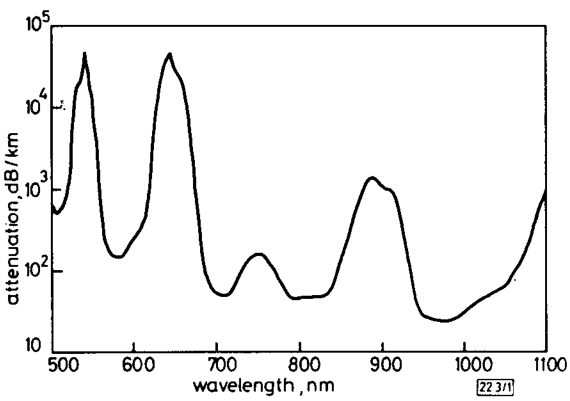

Fig. 1 *Spectral attenuation of holmium filter fibre*

1000 parts in 10^6 Ho^{3+}, an NA of 0·2 and a cutoff wavelength of 600 nm. The peak attenuation of 46000 dB/km, shown in Fig. 1, was measured by a cutback technique involving 1 m of fibre, while low-loss regions were measured with 20 m of fibre. From the Figure we see that there exist two major absorption bands, one of which conveniently blocks the 633 nm emission from an HeNe laser. Despite the presence of these large attenuation regions, a minimum loss of 25 dB/km at 980 nm is achieved.

For filter purposes it is essential that any light coupled into the undoped cladding and which would be transmitted by the fibre is removed. This was achieved by using a high-index acrylate primary coating.

Demonstration of filter performance: As a demonstration of the exceptionally high wavelength-dependent region of rare-earth-doped fibre filters, we have used the fibre to separate the anti-Stokes spontaneous Raman scattering from the pump wavelength in a short length of fibre. Detection of very weak scattering (or fluorescence) is normally limited by stray light falling on to the detector from the excitation source. Wavelength separation using a single monochromator can be achieved with a rejection of $\sim 10^{-4}$, while a double monochromator may have a rejection of 10^{-6} at 10 nm separation from the excitation wavelength. The limitation is due to stray light scattered and reflected from the internal surfaces of the monochromator, and grating imperfections. On the other hand, a rare-earth-doped fibre absorbs unwanted radiation and re-emits it as fluorescence at a wavelength far beyond that of interest.

The anti-Stokes Raman scattering intensity from a pump beam in a fibre of length L is given by

$$P_R = \frac{2P_L \sigma L \Omega\, \delta\nu}{\exp\left(\frac{h\nu}{KT}\right)^{-1}}$$

where P_L is the pump power and σ is the peak Raman cross-section of fused silica[3] ($9{\cdot}5 \times 10^{-9}$/m sr m^{-1} at 633 nm). Here Ω is the solid angle of acceptance of scattered light (0·0268 sr in this fibre) and $\delta\nu$ is the spectral bandwidth of the detector system (25 cm^{-1}).

The experimental arrangement is shown in Fig. 2. A silica monomode fibre 20 m in length was used to generate forward-scattered anti-Stokes Raman from a 1 mW 633 nm HeNe pump source. The Raman intensity (616 nm) is $1{\cdot}03 \times 10^{-7} P_L$ and therefore, to fully reject the pump signal, a differential

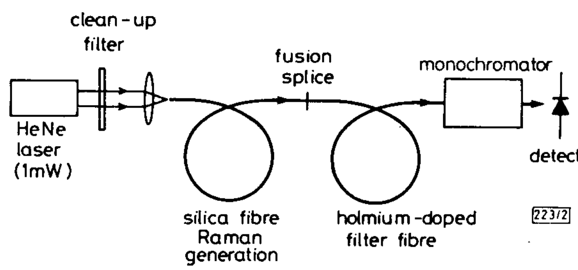

Fig. 2 *Experimental demonstration of fibre filter*

attenuation of about 10^9 is required. From Fig. 1 we see that, using a holmium-doped fibre, this is obtained with lengths greater than 5 m, and so a length of 7 m was chosen.

The undoped and doped fibres were fusion-spliced together with a loss estimated at 1 dB due to a mismatch of the fibre spot sizes. A multilayer dielectric filter (spectral width 10 nm centred at 633 nm) was used to remove unwanted emission from the pump laser which may have fallen within the passband of the holmium filter fibre. Thus only the pure 633 nm HeNe radiation was injected into the Raman-generating fibre.

The transmission of the 20 m Raman fibre and 7 m doped-fibre filter combination is plotted in Fig. 3. The edge of the

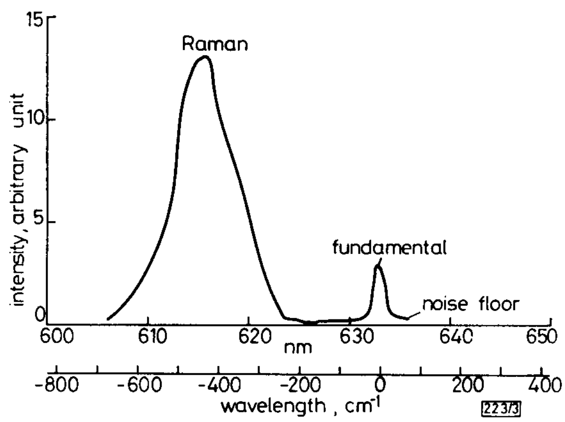

Fig. 3 *Transmission of fibre filter showing pump rejection and Raman transmission*

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spontaneous anti-Stokes scattering at 616 nm is seen to dominate all other emissions. Some transmission at 633 nm can be seen at 3×10^{-9} below input levels. Considerably greater rejection is obtainable if required with longer lengths of filter fibre. Transmission at all other wavelengths between 400 and 1000 nm was below 5×10^{10}, except for weak emission at 684 nm which corresponds to the 1183^{-1} Raman emission from silica.

Conclusions: We have shown that rare-earth-doped fibres can be used as optical filters with exceptionally high rejection. The filter has been demonstrated by detecting spontaneous anti-Stokes Raman light forward-scattered from an optical fibre, while blocking the exciting light to 10^{-9} of the initial value. We believe this is the first reported observation of spontaneous Raman scattering from an optical fibre in the forward direction. Suitably doped fibre absorption filters have a potentially wide range of uses.

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M. C. FARRIES
J. E. TOWNSEND
S. B. POOLE

Department of Electronics & Information Engineering
University of Southampton
Highfield, Southampton, Hants. SO9 5NH, United Kingdom

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