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Spectrally selective fundamental core mode suppression in optical fibre containing absorbing rods

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Abstract. **The feasibility of making a wavelength-selective fibre filter using fibre with absorbing rods in its silica cladding has been demonstrated theoretically for the first time. The technique described in this paper is of great practical interest for designing fibre lasers and amplifiers emitting at wavelengths where lasing is impeded by the presence of more energetically favourable radiative transitions in the active medium. In addition, the approach proposed here can be used for stimulated Raman scattering suppression. The unique feature of the fundamental core mode suppression mechanism examined is that there is a (bending) controlled spectral width of a region where excess losses are produced.**

Keywords: *optical fibre, fibre containing absorbing rods, wavelength-selective filter, resonance mode coupling.*

1. Introduction

For resolving a number of issues of practical importance (e.g. for producing ytterbium-doped fibre laser sources emitting at 976 nm, Nd-doped sources emitting near 920 nm, etc.), it is necessary to use wavelength-selective filters limiting the operating spectral range of the active medium. The use of bulk optics [1, 2] and local fibre components (e.g. Bragg gratings [3], spectrally selective media [4], and others) for this purpose allows the problem to be resolved only partially. The point is that, in this case, light is filtered not in the active fibre itself but at its output, when luminescence at undesirable wavelengths, amplified during propagation in the fibre, reduces laser efficiency. Besides, the use of additional components both increases the cost of the laser source and leads to a reduction in its efficiency (due to splice losses and light incoupling/outcoupling losses). In this respect, a direct increase in the optical loss of the operating core mode in an undesirable wavelength range has considerably greater potential because it alleviates the possibility of pump energy losses due to undesirable spontaneous luminescence amplification.

In particular, to optimise the Yb-doped fibre design for lasing at $\lambda \approx 976$ nm, Li et al. [5] proposed increasing the optical loss near 1030 nm using photonic bandgap fibre. One drawback to this approach is the low level of added losses, which requires increasing the core to cladding diameter ratio (in the case of cladding pumping) and using low rare-earth concentration in order to reduce the amplification rate at undesirable wavelengths as a function of active fibre length.

In this work, we propose an alternative approach to spectrally selective fundamental core mode suppression, using a technique reported previously [6], which relies on suppression of undesirable fibre core modes by embedding appropriate absorbing rods, with a refractive index above that of silica glass, in the cladding. Modifying the fibre cladding design changes the nature of the spectral dependence of the effective refractive index $n_{\rm eff}$ for some groups of modes. As a result, a pair of modes at particular (resonance) wavelengths can differ little in $n_{\rm eff}$ and have similar field intensity distributions (the two modes are localised in both the core region and the region of the absorbing rods). Mode shape distortion in such fibre increases the loss due to fusion splices with standard fibre, and the presence of strongly absorbing rods further increases the loss (as dopants for rods, one can use rare-earth elements [4] with strong absorption bands at the corresponding wavelengths).

In this paper, we theoretically demonstrate applicability of the technique in question [6] to fundamental core mode suppression in single-mode fibre, analyse how parameters of the absorbing rods influence spectral characteristics of the fibre structure, and assess the contribution of fibre geometry to guidance characteristics of the structure.

2. Formulation of the problem

In fibre design simulation, we used COMSOL Multiphysics software and in-house built software based on solving the scalar wave equation for a cylindrically symmetric waveguide structure [7]. In assessing $n_{\rm eff}$ as a function of wavelength, the material dispersion of the medium was left out of consideration and all calculated changes in $n_{\rm eff}$ were only due to mode coupling. The effect of fibre parameters (rod parameters) on guidance characteristics was studied for a particular case – resonance interaction wavelength $\lambda_{\rm res}$ near 1030 nm – which was of practical interest for Yb^{3+}-doped fibre lasers operating near 976 nm.

The fibre core parameters chosen corresponded to those of commercially available fibres and had low losses due to fusion splices with them. The fibre core diameter was taken to be 10 μm, and the core–cladding index difference was $\Delta n_{\rm core} = 0.002$. With these core parameters, the fibre was single-mode in the spectral range where fundamental mode propagation was to be suppressed. The diameter and refrac-

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tive index (RI) of the rods were chosen such that, in each particular case, the resonance peak position remained unchanged.

In Section 3, we examine how parameters of the absorbing rods influence characteristics of straight fibre: spectral width of the resonance interaction region (where fundamental mode distortion is observed) and the fraction of the core mode power captured by a rod at near-resonance wavelengths. To make results easier to interpret, we consider optical fibre containing only one absorbing rod. It has only two eigenmodes. At wavelengths far from resonance, one of them is localised predominantly in the core, and the other, in the rod.

In Sections 4 and 5, we consider the effect of a bend on spectral characteristics of the fibre and assess the potential of using the resonance mode coupling approach in a particular case of lasing in an Yb-doped medium at wavelength near 976 nm.

3. Straight fibre

To assess the effect of fibre structure geometry on guidance characteristics of the fibre, we numerically calculated the $n_{\rm eff}$ of modes propagating in the core–absorbing rod system. In addition, we estimated the fractions of the powers of these modes localised in both the rod and core regions. In this study, calculation was made for structures differing in the distance S from the rod axis to the fibre axis (at a constant RI of the rod relative to that of silica, Δn) and also for structures differing in Δn (at constant S). Moreover, in each case we calculated the $n_{\rm eff}$ of the eigenmodes of fibre having only a core (with no rod) and fibre having only a rod (with no core). The calculation results for one of the fibre designs under consideration are presented in Fig. 1.

It follows from the calculation results (Fig. 1a) that, far from resonance, the $n_{\rm eff}$ of the modes propagating in this system is essentially identical to the $n_{\rm eff}$ of the independent mode of the core (in the rod-free structure) and the $n_{\rm eff}$ of the independent mode of the rod (in the coreless structure). Moreover, the intersection point of the $n_{\rm eff}$ curves for the independent structures corresponds with good accuracy to the spectral position of the resonance. This finding has an important practical implication because such behaviour of $n_{\rm eff}(\lambda)$ means that, optimal parameters of the rods, ensuring resonance interaction with the core mode at a given wavelength, can be calculated by merely examining two independent cylindrically symmetric structures. Near the resonance wavelength $\lambda_{\rm res}$, the behaviour of the $n_{\rm eff}$ of both modes (the eigenmode of the core and that of the rod) changes. Direct calculations of the fraction of the power of the modes in each structure component (Figs 1b, 1c) shows that, at wavelengths above $\lambda_{\rm res}$, the intensities of both modes redistribute, and the mode initially localised predominantly in the core, moves to the rod region and vice versa. Near $\lambda_{\rm res}$, we observe degeneracy of the coupled modes, and the fractions of the powers of the modes propagating in the region of the absorbing rod become equal. Because of this, for uniqueness of definition the mode localised predominantly in the fibre core at a given wavelength (thick solid lines in Figs 1a and 1b) will be referred to as the core mode, and the mode localised predominantly in the absorbing rod (dotted lines in Figs 1a and 1b) will be referred to as the mode of the absorbing rod.

Analysis of the present results indicates that the width of the resonance interaction region (at constant parameters of

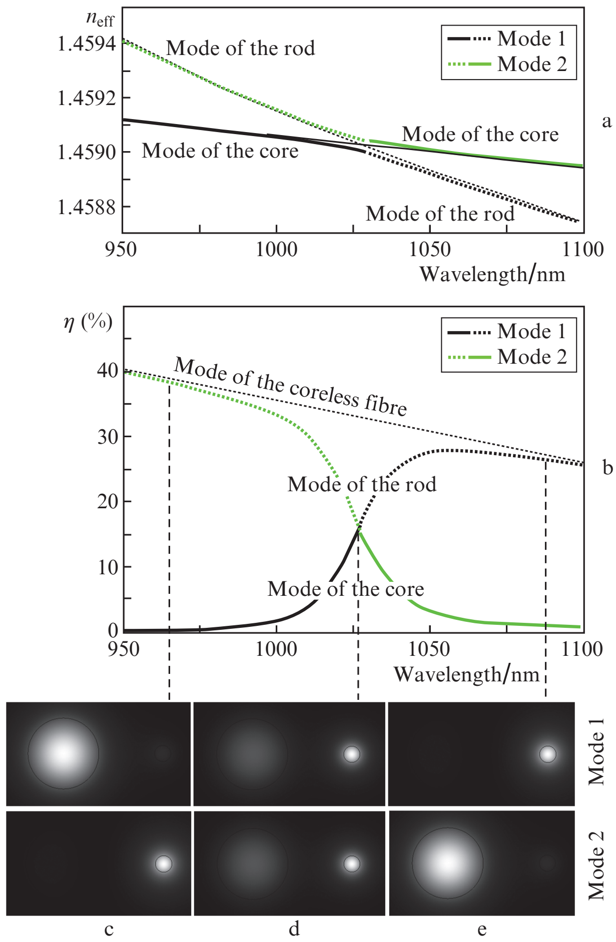

Figure 1. Wavelength dependences of (a) $n_{\rm eff}$ for fibre eigenmodes and (b) the fraction of the power of these modes in the rod. For each mode, some of the data are represented by a thick solid line if the mode is localised predominantly in the core, and some, by a thick dotted line if the mode is localised predominantly in the rod [thin black (solid and dashed) lines represent the $n_{\rm eff}(\lambda)$ and $\eta(\lambda)$ data for eigenmodes of the fibres (with no rod or core)]. 2D images of the electric field intensity distribution of modes propagating in the fibre at different wavelengths: (c) before resonance, (d) at resonance, and (e) after resonance.

the core) depends on the RI of the rod and its position relative to the fibre axis (Fig. 2). Increasing the rod–core index difference leads to changes in the wavelength dependence of $n_{\rm eff}$ and a decrease in the resonance interaction region (Fig. 2b). If the parameters of the rod approach those of the core, we observe the maximum broadening of the mode coupling region because the wavelength dependences of $n_{\rm eff}$ become as close to each other as possible. It is of interest to note that the maximum core mode power captured by the rod is only determined by the RI of the rod. This is clearly seen from comparison of Figs 2c and 2d: the fraction of the power in the rod changes only in response to changes in its RI. The fraction of the power of the fundamental mode in the region of the rod at resonance is then approximately 50% of the fraction of the power in the fibre containing only an absorbing rod (Fig. 1b). According to calculations, increasing the Δn of the absorbing rod (at constant position of the rod relative to fibre axis and a rod diameter ensuring resonance with the core mode at constant wavelength) leads to a decrease in the intensity of the resonance.

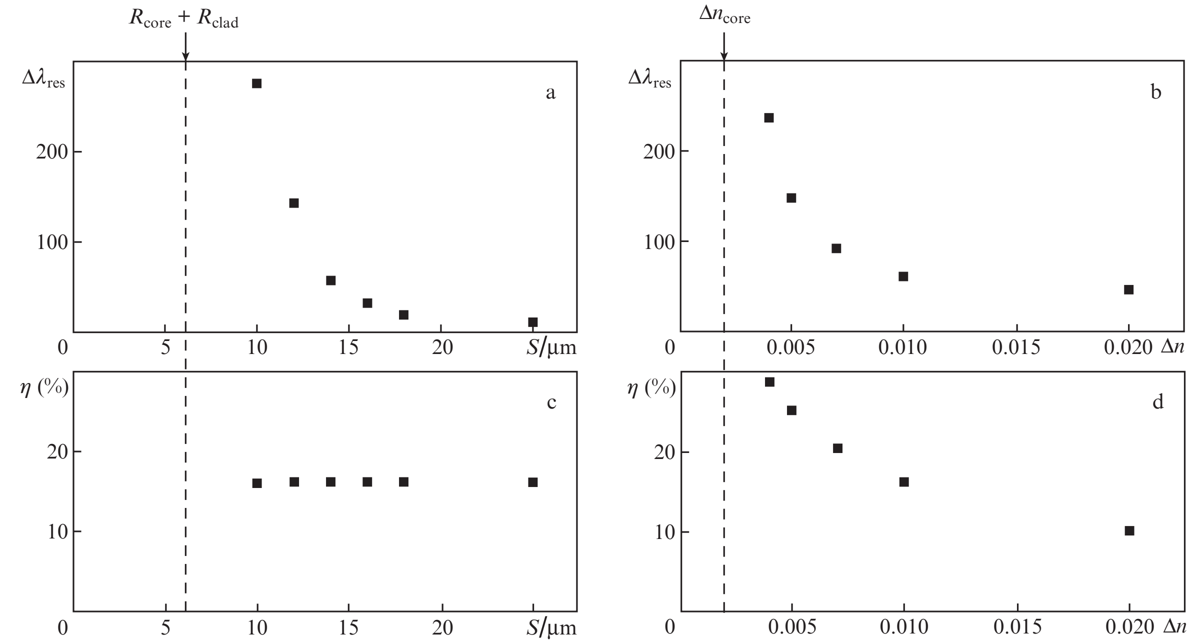

Figure 2. (a, b) 10-dB width of the resonance interaction peak and (c, d) fraction of the power of the fundamental mode propagating in the region of the rod, η, as functions of (a, c) the distance S between the rod and fibre axes and (b, d) the Δn of the rod; $R_{core} + R_{clad}$ is the minimum distance between the fibre and rod axes.

4. Bent fibre

As shown above, the resonance interaction spectrum depends on the spatial position of the absorbing rod and the Δn value chosen. Besides, an increase in the width of the resonance peak is in general accompanied by degradation of the optical loss contrast (the ratio of the losses at the wavelength being suppressed and the operating wavelength). At the same time, to resolve some issues of practical importance it is often necessary to ensure a strong absorption in a given spectral range, rather than at one wavelength, in combination with a large difference in optical loss between the operating wavelength (where the loss should be low) and the wavelengths where light should be suppressed. For example, in the case of Yb lasers emitting near 977 nm, low optical losses at this wavelength and high optical losses in the range 1000–1100 nm are needed.

Bending optical fibre changes resonance conditions, so it can become one of the ways to extend the spectral range of excess losses. A bent fibre design was simulated using a well-known RI profile modification technique [8, 9]:

$$n_b \approx n_{str}(1 + x/R_b),$$

where x is a spatial coordinate; R_b is the bend radius; and n_b and n_{str} are the RIs of the bent and straight fibre, respectively. Like in the case of straight fibre, we examined a single-rod fibre design. Since the bend direction influences characteristics of cylindrically asymmetric fibre, we examined two bend directions, corresponding to different states of the absorbing rod (Fig. 3a, inset). It is seen in Fig. 3a that stretching the absorbing rod causes a decrease in resonance wavelength, leading to a reduction in the width of resonance interaction and an increase in its intensity. Compression of the rod has

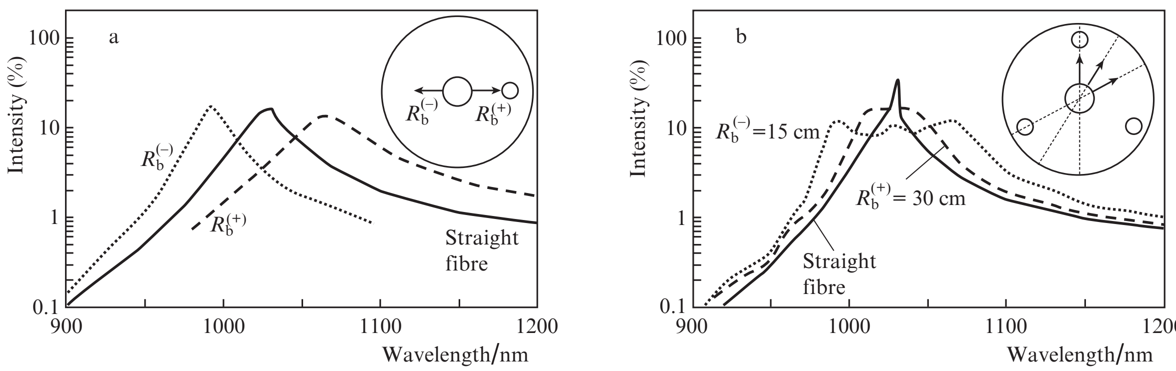

Figure 3. (a) Local fundamental mode suppression spectra of fibre containing one absorbing rod and (b) average fundamental mode suppression spectrum of fibre containing three absorbing rods. The arrows in the insets indicate the bend direction.

the opposite effect. Such behaviour is easy to understand by analysing how the RI profile of the modified fibre varies with bend radius. Rod stretching leads to a formal increase in the $n_{\rm eff}$ of the rod mode (a situation similar to an increase in the RI of the rod) and all subsequent changes associated with an increase in the RI of the rod.

Increasing the distance from the rod to the fibre axis and/or using high-index rods also increases the distinction between the modified RI profile of the bent fibre and the RI profile of the straight fibre, leading to even larger changes in resonance peak parameters.

Thus, we are led to conclude that bending a fibre containing one rod causes only a local change in resonance interaction peak position. Therefore, since the position of the rod relative to the bend direction cannot be uniquely determined under real conditions and also because of specific features of the fibre drawing process (fibre can become twisted during the drawing process), the spectrum of a bent fibre of constant length should be viewed as an average spectrum corresponding to all bend directions. As a result, the resonance interaction region of bent fibre turns out to be broader than that of straight fibre, and the resonance width depends on the bend radius.

In the case of fibre containing at least three absorbing rods, located at the vertices of an equilateral triangle, essentially any bend direction leads to differently directed shifts of the peak for all the rods. Because of this, the average absorption spectrum of bent fibre has a nearly rectangular shape (Fig. 3b). Besides, it is worth noting that varying the position of the rods relative to the fibre axis allows one to tune the bend sensitivity of the broadening of the resonance region and, accordingly, to control the width of the spectral region where fundamental mode propagation should be suppressed.

It is also worth noting that, near the resonance interaction wavelength, optical fibre whose cladding contains waveguiding rods has an anomaly in its dispersion curve, which shows up as resonance waveguide dispersion 'surges' towards anomalous and normal dispersions on both sides of the resonance wavelength (Fig. 4). The reason for such a wavelength dependence of dispersion is that, in the resonance interaction region, the core mode is considerably distorted and the effect of waveguide structure geometry on the operating mode propagation velocity in a waveguiding medium is no longer negligible. At the resonance wavelength, there is an uncertainty due to the degeneracy of coupled modes in terms of the effective refractive index and mode field intensity distribution of the core and rod. Bending optical fibre causes not only broadening of the core mode suppression band but also a shift of dispersion curves (Fig. 4).

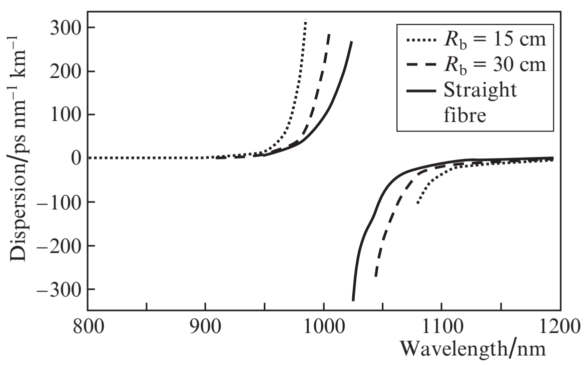

Figure 4. Calculated waveguide dispersion of the core mode near the resonance wavelength for a straight and a bent fibre.

5. Amplifier (λ = 976 nm) based on Yb-doped optical fibre containing absorbing rods

To verify the applicability of the proposed technique for the filtering of spectral components generated by an active medium, we analysed the effect of added losses on the output characteristics of a cladding-pumped 0.98-μm Yb-doped fibre amplifier with the copropagating pump and signal configuration. To this end, we solved rate equations [10] that took into account forward and backward luminescence amplification and evaluated the change in the operating length of the active fibre and pump conversion efficiency. In our calculations, the signal wavelength was taken to be 976 nm, and the core and cladding diameters were 10 and 80 μm, respectively.

The operation of the amplifier was studied at two radially uniform concentrations of Yb^{3+} ions introduced into the silica glass network: 1.5×10^{25} and 3×10^{25} m^{-3}. The core material was photodarkening-free phosphosilicate glass [11]. Absorption and emission cross sections were borrowed from Melkumov et al. [12]. Another possible core material is phosphoaluminosilicate glass with a slight phosphorus excess [13], which allows the photodarkening loss to be minimised [14]. The signal power at the amplifier input was taken to be 100 mW, which corresponded to the saturation power. The spectrum of the loss due to resonance mode coupling was taken to have a rectangular shape, with zero loss at wavelengths from 900 to 990 nm and a loss determined by the fibre design in the spectral range 990–1100 nm.

According to our calculations, increasing the level of losses leads to an increase in pump-to-signal power conversion efficiency. Note that the factor determining the increase in pump efficiency is the total loss accumulated during signal propagation along the length of the active fibre. The use of fibre with a lower dopant concentration in its core and the corresponding choice of the active fibre length at constant pump-to-signal power conversion efficiency make it possible to employ fibre with a lower level of added losses for fundamental mode suppression. Increasing the loss in the spectral range where the core mode should be suppressed leads to a nonlinear rise in conversion efficiency and, at a certain level of losses it reaches saturation, obviously due to the fact that amplified spontaneous emission is almost completely suppressed and essentially all active ions emit near 0.98 μm (Fig. 5).

Thus, we are led to conclude that spectrally selective operating fibre mode suppression allows pump-to-signal conversion efficiency to be raised. In this process, the loss induced in a given spectral range and necessary for maximising efficiency is determined by the active element concentration in the silica glass network.

6. Conclusions

We have examined selective suppression of operating core mode propagation in a given spectral range via mode shape distortion and absorption in optically denser rods incorporated into the silica fibre cladding. The fibre design can generally include any number of rods, but, as shown in this study, even three absorbing rods are sufficient for the absorption spectrum induced in the spectral range chosen to have a

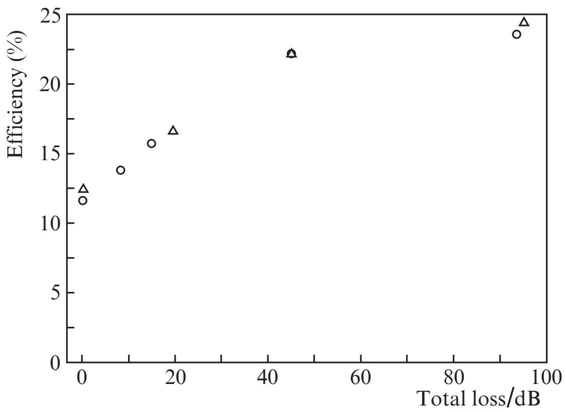

Figure 5. Pump-to-signal power conversion efficiency as a function of added loss in the spectral range above 990 nm for the copropagating amplifier configuration at Yb^{3+} dopant concentrations of 3×10^{25} (open circles) and 1.5×10^{25} m^{-3} (open triangles).

nearly rectangular shape. An important practical aspect of the proposed technique is that the width of the loss spectrum can be controlled by varying the fibre bend radius. Bend sensitivity of the absorption spectrum can be set by choosing the refractive index of the absorbing rod and the distance from it to the fibre axis. Thus, the fibre design with absorbing rods is indeed sufficiently flexible from the viewpoint of guidance characteristics of the structure and places no stringent requirements for the fibre fabrication process. Possible mistakes in structure fabrication can be compensated for by drawing fibre to an appropriate diameter (rough tuning of the resonance peak position) and choosing the fibre bend radius (fine tuning), which allows the absorption band to be shifted to a preset wavelength. The technique proposed in this work makes it possible to control the width and position of the resonance absorption spectrum for resolving each particular problem.

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