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Quasi-single-mode hybrid fibre with anomalous dispersion in the 1 μm range

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Abstract. **We have proposed and demonstrated an approach for ensuring quasi-single-mode operation of a cylindrically symmetric hybrid fibre having anomalous dispersion at wavelengths around 1 μm. Basic to this approach are distinctions between spatial fibre mode distributions and the use of a high-loss ring layer in the region of a minimum in the electric field of the operating hybrid mode.**

Keywords: *optical fibre, hybrid fibre, single-modedness, dispersion compensation, dispersion-shifted fibre, selective mode suppression.*

1. Introduction

The lack of commercially available optical fibres with anomalous dispersion at wavelengths around 1 μm is one of the main factors that limit the possibility of making all-fibre lasers with pulse durations shorter than 1 ps in this spectral range. Dispersion compensation in the 1 μm range is typically ensured by bulk components (gratings and prisms), but such an approach significantly reduces the reliability of lasers.

To solve this problem, a number of specialty fibre designs that ensure anomalous dispersion in the 1 μm range have been proposed to date: microstructured fibres [1 – 3], air-core fibres [4, 5] and few-mode fibres in which a higher order mode is excited using a long-period grating [6, 7]. However, the use of these types of fibre presents some difficulties. In particular, microstructured fibres are highly nonlinear (the core size needed to obtain anomalous dispersion typically does not exceed 3 μm). Air-core fibres operate in the few-mode regime and the main difficulty in dealing with them is that selective excitation of the fundamental mode is necessary (input beam alignment and mode field size matching are needed). Moreover, splicing such fibres to beam delivery fibres presents serious difficulties or requires specially designed equipment, because the holes forming the air-core fibre structure collapse on heating. In the few-mode fibres proposed by Nicholson et al. [6] and Ramachandran et al. [7], operating-mode excitation requires long-period gratings, but optimising their parameters and writing them is a separate complex technical problem. Moreover, when this approach is used, it is essentially impossible to guarantee that the fundamental mode will be completely converted into an operating higher order mode and back again. As a consequence, a small fraction of the power can propagate in the fundamental mode after passing through a long-period grating. As a result, a second pulse will be generated in the fibre, which will have lower intensity and differ in velocity from the main pulse.

Previously, we proposed a new type of optical fibre, a so-called hybrid fibre, with anomalous dispersion at wavelengths around 1 μm [8]. The operating mode of such fibre is formed via coherent Fresnel reflection from one or several ring layers which are optically denser than their core (similarly to Bragg fibre [9]). A distinctive feature of the hybrid fibre relative to Bragg fibres is that the refractive index of its core exceeds that of undoped silica glass. Thus, owing to the total internal reflection mechanism, the operating mode has zero leakage loss. In other words, the propagation loss of this mode is only determined by the fundamental mechanisms characteristic of step-index fibres [8]. As a result, the formation and propagation of the operating mode in a hybrid fibre are due to two independent mechanisms. Accordingly, the operating mode of the fibre will be referred to as a hybrid mode. Even though such fibres are formally not single-mode, only the hybrid mode is localised directly in their core and the intensity peaks of the other fibre modes are shifted to the region of the optically denser ring layers.

The splicing of a hybrid fibre to a standard single-mode fibre leads to predominant excitation of the hybrid mode confined in the fibre core. Another important property of the proposed fibre design is that the hybrid mode can have anomalous dispersion at wavelengths around 1 μm [8, 10]. The use of such hybrid fibre allowed us to demonstrate chirped 8-ps pulse compression to about 330 fs in the 1 μm range [8]. Nevertheless, partial excitation of the modes confined in the ring layers adjacent to the fibre core (with their power reaching 10% to 20% of the total power) prevented us from obtaining single-pulse laser operation. The autocorrelation traces of pulses typically had several peaks of different intensities, indicating that two or more modes propagated through the core at different group velocities. Figure 1 illustrates the effect of hybrid fibre length on the observed pulse duration.

In this work, we demonstrate how quasi-single-mode operation of a hybrid fibre can be achieved. The effectiveness of the proposed approach is illustrated by the example of a hybrid fibre design with two optically denser ring layers, which allows an anomalous dispersion up to 100 ps nm^{-1} km^{-1} to be reached at wavelengths around 1 μm.

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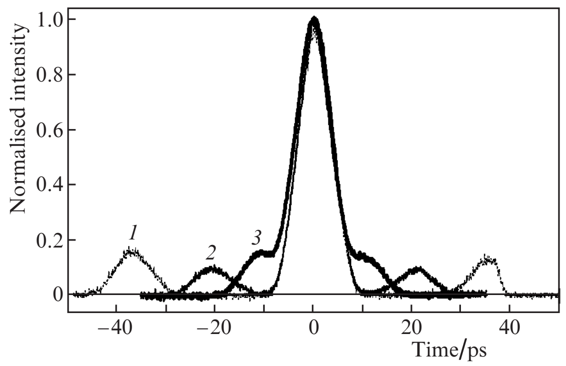

Figure 1. Pulse durations evaluated from autocorrelation traces at the output of a cylindrically symmetric hybrid fibre (*1*) 3, (*2*) 1.5 and (*3*) 0.7 m long that was used as a chirped pulse compressor.

2. A method for unwanted mode suppression in a hybrid fibre and fibre design

To suppress unwanted modes in a hybrid fibre, we take advantage of the fact that the electric field distribution across the fibre varies from mode to mode. Figure 2a shows a model refractive index profile of a hybrid fibre with a dispersion of about 100 ps nm^{-1} km^{-1} at a wavelength of 1.06 μm (Fig. 2b). Also shown in Fig. 2a are the radial electric field distributions of the hybrid mode LP$_{03}$ and two other modes that have field maxima in the optically dense layers. It is seen that the LP$_{03}$ mode intensity has two minima, one in the region of the fibre core (on the boundary of a highly Ge-doped layer) and the other between the highly Ge-doped layers. The basic idea behind the proposed approach is to insert a layer with excess losses in one of the electric field minima of the hybrid mode. The increase in the optical loss of the hybrid mode will then be minimal, whereas the optical losses of the other (unwanted) modes will increase sharply, because the fraction of their power in the region of the absorbing layer considerably exceeds that of the operating hybrid mode.

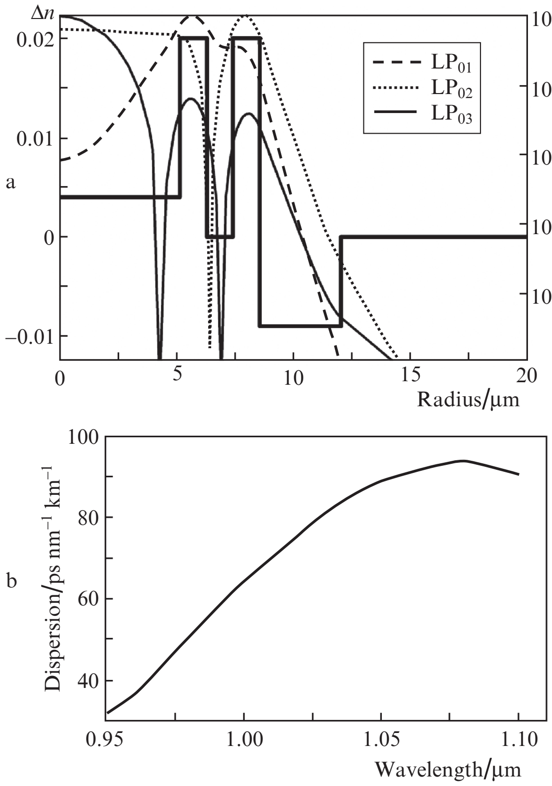

Figure 2. (a) Model refractive index profile of a hybrid fibre, calculated electric field distributions of the hybrid mode LP$_{03}$ and a few modes of the ring layers and (b) calculated dispersion curve of the LP$_{03}$ mode for the model index profile.

Our calculations demonstrate that the spatial localisation of the mode field minimum situated between the highly Ge-doped layers is less sensitive to bends and changes in operating wavelength than is the minimum in the region of the fibre core (Fig. 3a). As a consequence, it is between the high-index layers where the ring layer with excess losses should be located in order to maximise the operating spectral range of the hybrid mode and concurrently to suppress the unwanted modes of the fibre.

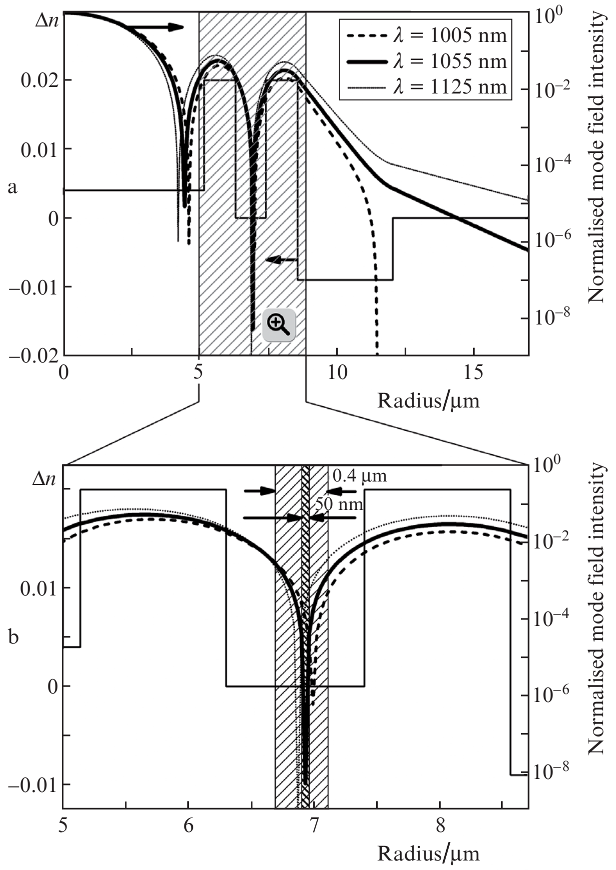

Figure 3. (a) LP$_{03}$ mode field intensity distributions in the structure of a hybrid fibre at wavelengths of 1005, 1055 and 1125 nm; (b) enlarged region of the minimum in the LP$_{03}$ mode field intensity between the optically dense ring layers.

To minimise the propagation loss of the hybrid mode and concurrently to maximise the losses of the other modes, a layer as narrow as possible with the highest possible level of added loss should be inserted into the structure. The problem of obtaining high optical losses in a thin ring layer is nontrivial in itself. Two fundamentally different approaches can be used to resolve it: either an excess scattering or excess absorption should be ensured in the layer. Note that, to ensure an excess scattering, the glass should in fact be phase-separated. This approach is sufficiently attractive and makes it possible to reach optical losses at a level of tens of dB km^{-1} [11], or even hundreds of dB km^{-1} with optimised glass composition.

To obtain the highest possible absorption coefficient, we optimised the glass network composition. We considered silica glasses doped with chromium, samarium and lead ions. To evaluate the maximum absorption that can be reached with a particular dopant, we prepared step-index test fibre preforms by the MCVD process. The dopants were introduced by the solution doping technique. The preforms were drawn into single-mode fibres. The propagation loss in the spectral region around 1 μm was determined by consecutively reducing the fibre length (cut-back technique).

It is known from the literature [12] that the Cr^{4+} ion in glasses of various compositions has a broad absorption band in the visible and near-IR spectral regions. At the same time, chromium ions can also have a valence of 3+ or 6+, depending on the host glass composition and preparation conditions. As a result, the near-IR absorption of chromium in glass hosts can be considerably reduced. Loss measurements in a test fibre with a chromium-doped core showed that the loss at a wavelength near 1 μm did not exceed 0.02 dB m^{-1}. With lead ions as an absorbing dopant in a germanosilicate host, we also failed to reach an appreciable absorption: it did not exceed 0.03 dB m^{-1}. The use of Sm^{3+} for hybrid fibre mode selection was prompted by the fact that this ion has characteristic strong absorption bands at wavelengths around 1 μm. The propagation loss in the core of such fibre was ~400 dB m^{-1} at a wavelength of 1.064 μm.

To assess the effect of absorbing layer thickness on the optical loss in each mode, we performed theoretical calculations. In particular, we first considered the case where the thickness of the selective layer was 50 nm and the loss in the mode fully confined in this layer was 400 dB m^{-1} (Fig. 3b). According to the calculation results, the level of losses for the operating hybrid mode can be reduced in such a case to the level of fundamental losses and the losses for the unwanted fibre modes may exceed the loss for the LP$_{03}$ mode by almost 30 dB (Fig. 4a). It is worth noting that such a fibre design is rather difficult to implement in practice. One reason for this is diffusion in the course of fibre drawing. Moreover, even if such a layer were successfully produced, there remains the problem of exactly reproducing the model index profile in practice. A slight displacement of the high-loss layer with respect to its optimal position will significantly degrade the selectivity of the fibre design. It is also worth noting that, at the above level of losses in the absorbing layer, the losses of the unwanted fibre modes (e.g. in LP$_{02}$) do not exceed 1 dB m^{-1} (Fig. 4a). Because of this, effective mode filtering can only be achieved at a sufficiently long length of the fibre (over 10 m). In most cases, this approach is unacceptable because of the sharp decrease in the threshold for nonlinear effects with increasing fibre length.

Figure 4b shows the estimated loss for modes propagating in a hybrid fibre with a selective layer thickness of 400 nm. One advantage of this configuration is that the fibre length needed for effective unwanted mode selection is just a few metres. Unfortunately, it has a poorer selectivity for losses in modes: 13 dB. At the same time, the added optical loss is a rather weak function of wavelength (at a given level of absorption in the layer), which simplifies fibre design optimisation. In particular, varying the fibre core diameter allows the desired position of the maximum in anomalous dispersion to be obtained, without degrading the selectivity of the embedded layer.

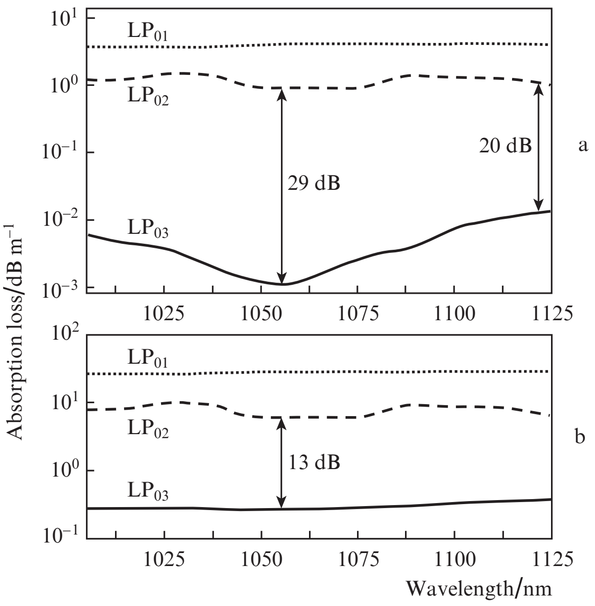

Figure 4. Calculated loss spectra of the LP$_{03}$, L$_{P02}$ and LP$_{01}$ modes in a hybrid fibre with a selective layer thickness of (a) 50 and (b) 400 nm.

3. Hybrid fibre fabrication

We examined two approaches to unwanted fibre mode suppression. Using the MCVD process, we produced hybrid fibre preforms containing a scattering layer from glass consisting of various phases and hybrid fibre preforms containing an absorbing layer. Analysis of their properties suggests that the incorporation of a scattering layer into the hybrid fibre design appears less attractive from the practical point of view. Phase separation was only ensured in glasses differing markedly in viscosity and thermal expansion coefficient from germanosilicate glass, which led to a severe distortion of the shape of the high-index ring layers (Fig. 5a). Because of this, excess losses due to scattering by the boundaries of the optically denser layers were observed for the hybrid mode as well. In particular, the level of losses in a fibre drawn from a preform having a scattering layer exceeded 5 dB m^{-1}.

The incorporation of an absorbing layer allowed us to obtain structures with a significantly better cylindrical symmetry (Fig. 5b). The absorbing layer was produced by introducing samarium ions into the germanosilicate glass network.

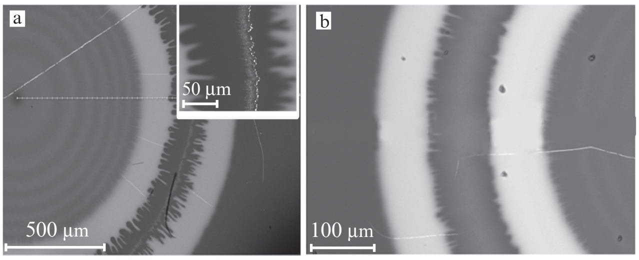

Figure 5. Cross-sectional SEM images of fibre preforms having (a) a scattering and (b) an absorbing selective layer.

The absorbing ligand distribution and the elemental concentration profile across the fibre preform were obtained using energy dispersive X-ray microanalysis on a JEOL JSM-5910LV scanning electron microscope (SEM) equipped with an Oxford Instruments AZtecEnergy EDX spectrometer system. Micrographs of the samples and their elemental composition were obtained using backscattered electron (Z-contrast) imaging. Standard deviations in elemental concentrations were ±0.07, 0.10, 0.01 and 0.03 wt % for Si, Ge, Sm and O, respectively. The samarium content of the absorbing layer was 0.08 at %. The preform was drawn into fibre 125 μm in outer diameter. Its polymer coating had a refractive index exceeding that of undoped silica glass. Figure 6 shows the measured refractive index profile of the fibre, an image of its end face and an approximated radial samarium concentration profile.

The mode composition was studied using a beam scanning technique: possible modes of the test fibre were excited by a single-mode beam scanned over the fibre end face. In assessing the mode composition of a fibre with a complex structure (as in the case of the hybrid fibre), a light beam incident on the fibre axis excites modes confined predominantly in the core region. Displacement of the excitation beam from the fibre axis leads to predominant excitation of modes localised in the periphery of the fibre structure (in the optically denser ring layers in the case of the hybrid fibre). The present results demonstrate that, at a wavelength of 1.064 μm, only the LP_{03} hybrid mode propagates at the output of the hybrid fibre if its length exceeds 5 m (Figs 7a–7c). When the excitation beam was shifted from the fibre axis, we observed only a gradual decay of the core mode. Bending the fibre (to a bend diameter of about 1 cm) did not cause any distortion of the mode or any variations in the intensity of the light propagating through the highly Ge-doped cladding layers. The mode field diameter was determined to be 5.4 μm. Analysis of the mode composition of a shorter piece (~0.5 m) of the fibre showed that the propagation of modes of the ring layers was possible: when the excitation beam was shifted from the fibre axis, we observed emission from the ring layers (Figs 7d–7f).

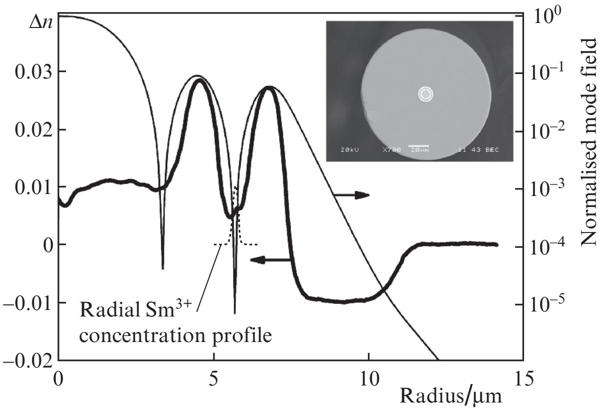

Figure 6. Measured refractive index profile of the hybrid fibre, the corresponding calculated field distribution of the operating hybrid mode and the radial samarium concentration profile (dashed line). Inset: image of the fibre end face.

Figure 8 shows the loss spectrum of the hybrid fibre measured by the cut-back technique and a characteristic absorption spectrum of samarium ions, normalised to the level of losses in the hybrid fibre. The loss measurements were made at a fibre length over 5 m, where the power of the unwanted modes in the fibre was negligible. The loss in the hybrid mode at 1.064 μm was determined to be ~0.8 dB m^{-1}. The loss due to the splicing of the hybrid fibre to a standard step-index fibre (core and cladding diameters of 6 and 125 μm, respectively) was 2.5 dB at a wavelength of 1.06 μm.

Dispersion was measured by an interferometric technique [13]. The measurement procedure required that a rather short piece (about 70 cm) of the test fibre be used, so that the excitation, propagation and detection of unwanted modes were quite probable. Because of this, to reduce uncertainty in our measurements the operating mode was selectively excited via splicing of the hybrid fibre to a standard step-index single-mode fibre and the signal was coupled into the single-mode fibre. Beam quality was monitored using an IR camera mounted at the output end of the hybrid fibre. After the net dispersion was measured, the dispersion of the spliced single-mode fibre was subtracted from the result. The measured dispersion of a segment of the fibre under study is shown in Fig.

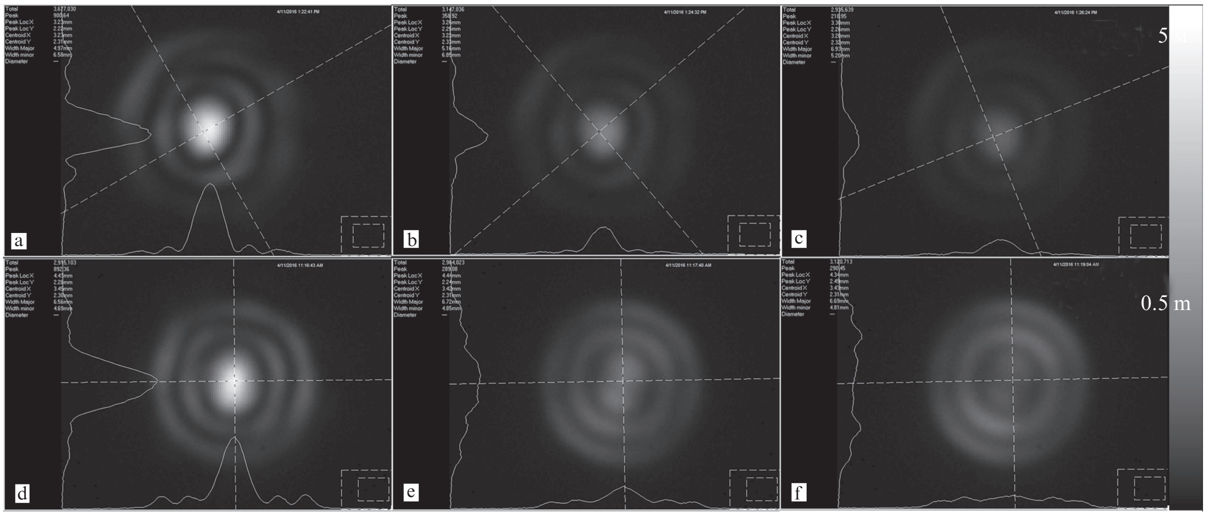

Figure 7. Measured mode composition at the output of a (a–c) 5 and (d–f) 0.5 m length of the hybrid fibre: (a, d) the excitation bean is incident on the fibre axis; (b, c, e, f) the beam is shifted from the fibre axis.

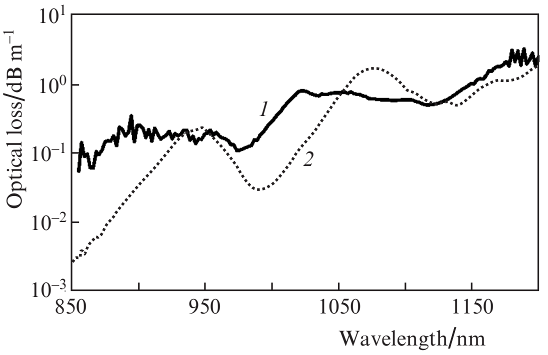

Figure 8. (*1*) Measured loss spectrum of the hybrid fibre and (*2*) characteristic absorption spectrum of samarium ions in a glass network.

9. The scatter in the dispersion data is caused by the narrow spectral range (~100 nm) of our measurements, which was limited by the possibility of exciting only the hybrid mode on the one hand (there were no higher order hybrid modes and no modes of the optically denser ring layers) and by the hybrid mode cutoff, located near 1200 nm, on the other.

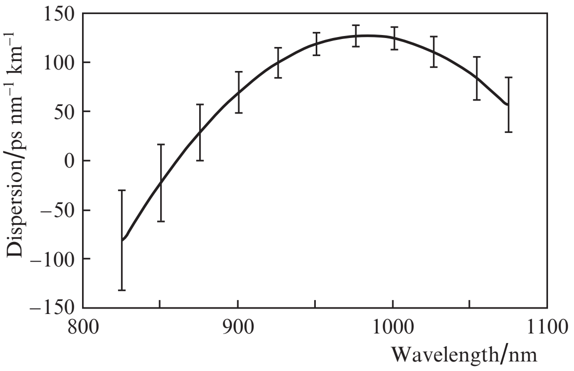

Figure 9. Measured dispersion of the hybrid fibre.

Thus, we have proposed and demonstrated a technique for suppressing unwanted fibre modes by inserting an additional, strongly absorbing layer in the region of a minimum in the operating mode of the structure. The effectiveness of the technique has been illustrated by the example of a cylindrically symmetric hybrid fibre with anomalous dispersion in the 1 μm range. The use of Sm ions as absorbing impurities allowed us to separate the operating mode from the other modes of the fibre owing to the difference in propagation loss, thereby ensuring effective filtering of the unwanted modes via selection of an appropriate fibre length.

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