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Single-mode fibre with an additional ring fibre for two-channel communication and special applications

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Abstract. **Two-channel concentric fibres with a broadband single-mode optical fibre operating at 1.3 μm and an additional multimode ring fibre of thickness 10 μm with an outer fibre diameter of 125 μm are developed for the first time for two-channel communication and special applications. Optical attenuation in the single-mode fibre and in the ring core was less than 1 dB km^{-1}, while the crosstalk attenuation between the channels was more than 40 dB. It is found that optical attenuation in the ring fibre depends on the radius of the bend and on the tensile force applied during winding of the fibre into coils. Optimal parameters of the refractive index profile are determined, in particular, the value of Δn for the ring for which the losses in the ring fibre on the coils as well as in the straightened state are minimal. A 12-km long fibre line is constructed and the distribution of attenuation over its length is analysed. It is shown that distributed coupling between the channels in such fibres is virtually absent and a high optical isolation between the channels is preserved.**

Keywords: *ring fibre, two-channel fibre, refractive index profile, crosstalk attenuation between channels, optical attenuation.*

1. Introduction

Fibres with a complicated refractive index profile are important for special applications because the properties of data transmission channels can be optimised and functionally modified by selecting the fibre parameters. Two-channel fibres with concentric geometry were proposed long ago [1 – 3]. Multimode cores and ring fibres were prepared and their parameters were chosen so that they ensured convenient pumping by radiation sources and an optical isolation between the channels at level of $\sim$ 20 dB, which was considered sufficient for separate transmission of digital and analogue luminous fluxes in systems of two-channel or duplex communication. Owing to their very small transverse size and weight and due to the fact that fibres are completely dielectric waveguides and are not subjected to electromagnetic interference, two-channel concentric fibres are of considerable interest for applications in aviation, space crafts, communication systems and telecontrol of moving objects, and for some other applications.

It is important that concentric preforms for fibres can be fabricated using the well-developed MCVD technology [3] and pulling can be performed using the same equipment as for traditional communication fibres. The outer diameter of fibres used in Ref. [1] (180 μm) differs from the diameter of standard fibres only by 55 μm, which makes it possible to splice such fibres into a line using the conventional welding technology. To facilitate the coupling with radiation sources, the core diameters were usually chosen in the range 20 – 30 μm and the ring was removed to a distance no less than 20 μm to provide the required optical isolation between channels and to reduce the effect of technology on losses and crosstalk.

Another variety of concentric fibres is a single-mode fibre with an auxiliary thin ring fibre (tube) which is placed at a short distance (less than 10 μm) from the single-mode core. The operation of such a two-channel fibre is based on the distributed coupling between the channels, which is realised for close or equal propagation constants, leading to radiation transfer from the core to the ring and back, which is periodic over the fibre length. The properties of such coaxially coupled fibres were considered in Ref. [4] on the basis of the Marcuse theory [5] in order to investigate the possibility of creating fibre sensors on their basis with distributed coupling controlled by an external physical action.

The aim of this work is to develop and study two-channel concentric fibres with a structure differing from those studied in the above mentioned works [1 – 4]. The core of this structure is a single-mode fibre operating at 1.3 μm, while the additional ring fibre with a ring width $\sim$ 10 μm is separated from the core by a distance ensuring the maximum optical isolation between the channels (preferably, within the range 40 – 70 dB) for an outer diameter of the fibre of 125 μm. With such a fibre geometry, broadband data transmission can be carried out through the single-mode core, and control and measuring information, as well as control commands or interactive communication signals can be transmitted in the forward or backward direction through the ring fibre.

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The main problems encountered in designing such fibres are the achievement of a proper optical isolation of the channels and of low optical losses, as well as the fabrication of devices for independent input and extraction of information from the channels. It is also important to be able to splice such fibres into a line like ordinary communication fibres using a standard welding apparatus, which would permit their practical application. The concentric geometry meets these requirements to the fullest extent.

An advantage of the fibre construction considered here is the possibility of carrying out a preliminary theoretical analysis of its parameters. Due to the coaxial structure of a two-channel fibre with a single-mode fibre at the centre, the number of model equations used for numerical simulation of such fibres before working out their fabrication technology is substantially reduced. The structure of the two-channel fibre proposed by us here considerably differs in this respect from the earlier versions with multimode fibres at the centre and in the ring, for which general considerations of the waveguide theory had to be used or considerable simplifying assumptions had to be made in a theoretical analysis, making the predicted results unreliable.

In our case, the theoretical problem was solved rigorously. This allowed us to fabricate the fibres in technological processes, to measure their main optical properties, and to manufacture two-channel concentric fibres with low losses (~ 1 dB km^{-1}) both in the single-mode core and in the ring core. The optical isolation of the channels in this case was no lower than 40 dB.

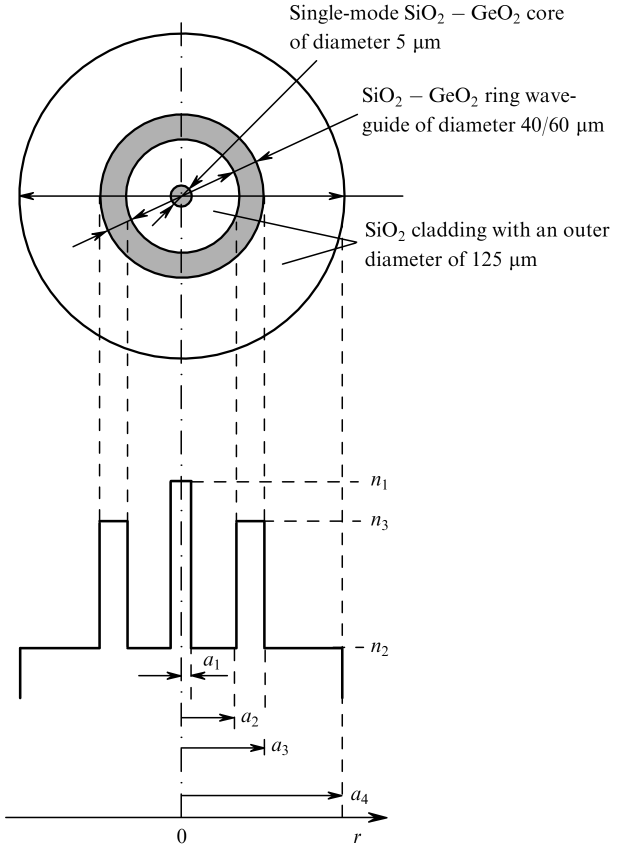


Figure 1. Cross section and refractive index profile $n(r)$ of a concentric two-channel fibre.

2. Numerical simulation and analysis of crosstalk attenuation

The main problems in numerical simulation is the calculation of the dispersion parameters of the single-mode core taking into account the presence of a lightguiding ring and the analysis of the crosstalk attenuation α_{cr} and α_{rc} from the core to the ring and from the ring to the core, respectively, as functions of the width and the radius of the ring. In Ref. [2], the crosstalk was calculated for a more general case of a multichannel concentric fibre consisting of alternating layers with different optical densities using the theory of weakly coupled waves and recom-mendations were given for choosing the waveguide parameters. It is clear that to increase the crosstalk attenuation in our case, the diameter of the single-mode core should be reduced and the refractive index difference Δn_c in it should be increased. The refractive index profile of the fibre proposed by us is shown in Fig. 1. We provided the condition $\Delta n_c > \delta n_r$ (the refractive index difference of the ring), to make the principal HE_{11} mode of the single-mode fibre not a leaky mode at the bends.

For the cylindrical geometry of the fibre, the transverse field components E_r, E_φ, H_r, H_φ can be expressed in terms of the longitudinal components E_z and H_z [6]. The expressions for the longitudinal components of the modes of the multilayered fibre in the fibre layers of the core and the ring under investigation with large Δn_c and Δn_r have the form

$$E_{zi} = A_i J_i(k_i r) + B_i N_n(k_i r),$$
$$H_{zi} = C_i J_n(k_i r) + D_i N_n(k_i r), \tag{1}$$

where J_n and N_n are Bessel functions of the first and second kind, respectively, and

$$k_i^2 = k_0^2\left(n_i^2 - n_{\text{eff}}^2\right) > 0 \tag{2}$$

is the square of the wave number of the mode in the ith layer of the fibre; $k_0 = 2\pi/\lambda$; $n_{\text{eff}} = c/\upsilon_{\text{ph}}$ is the effective index of slowing down of the phase velocity υ_{ph} of the mode; and c is the speed of light.

Outside the fibre core, we have the following expressions for the field components in cladding layers with a smaller refractive index:

$$E_{zi} = A_i I_n(k_i r) + B_i K_n(k_i r),$$
$$H_{zi} = C_i I_n(k_i r) + D_i K_n(k_i r), \tag{3}$$

where I_n and K_n are modified Bessel functions of the first and third kind, and the wave number of the modes in this case satisfies the condition

$$k_i^2 = k_0^2\left(n_{\text{eff}}^2 - n_i^2\right) > 0. \tag{4}$$

For a fibre with $\Delta n_c > \Delta n_r$, we should assume that $B_1 = D_1 = 0$ to satisfy the condition of the finite field on its axis, while for the outer layer of the fibre, we should assume that $A_n = C_n = 0$ to satisfy the condition for the emission of the mode field at infinity.

Using the physical boundary conditions for the fibre structure under study, we obtain the characteristic equation whose solution gives n_{eff}.

For fibres with an arbitrary refractive index profile, we worked out a program for calculating n_{eff} for various types of modes including the HE_{11} mode, which also took into account the dependence of the refractive index of the fibre material on the wavelength λ [7]. The dispersion coefficient for the HE_{11} mode was calculated using the rigorous formula

$$S = -\frac{\lambda}{c}\frac{d^2 n_{eff}}{d\lambda^2}. \quad (5)$$

This formula is valid for any Δn and takes into account the material and wave dispersions.

The calculations were made for fibres with the following parameters: the core of diameter $2a_1 = 4$ μm made of $SiO_2 - GeO_2$ (molar concentration 9 %), $n_1 = 1.4623$ for $\lambda = 1.3$ μm; the inner radius of the ring $a_2 = 20$, 25, 30, or 35 μm; fibre ring of thickness 15 μm made of $SiO_2 - GeO_2$ (molar concentration 5.46 %) with $n_3 = 1.4548$; and undoped intermediate layers made of SiO_2 with $n_2 = 1.4473$. The outer diameter $2a_4$ of the fibre was 125 μm. For this fibre, $\Delta n_c = n_1 - n_2 = 0.015$, $\Delta n_r = n_3 - n_2 = 0.0075$ and the numerical aperture of the ring fibre was $NA = (n_3^2 - n_2^2)^{1/2} = 0.1475$ for $\lambda = 1.3$ μm.

Fig. 2 shows the dependence of the dispersion coefficient S on λ for the fibre under study. For $\lambda = 1.3$ μm, we obtain $S = -2.62$ ps nm^{-1} km^{-1}; this value is virtually independent of the ring diameter for $a_2 = 20 - 30$ μm.

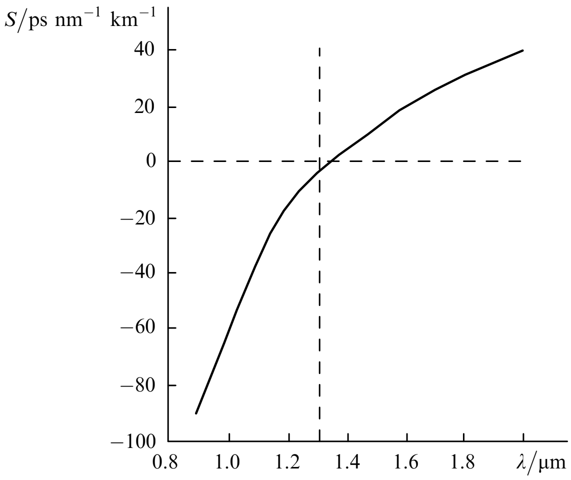


Figure 2. Calculated dependence of the dispersion coefficient S on the wavelength λ for the single-mode core with an additional ring waveguide in the concentric structure of a fibre with an outer diameter of 125 μm.

The normalised power P_r of the HE_{11} mode propagating in the ring layer of thickness $a_3 - a_2 = 15$ μm determines the crosstalk attenuation from the single-mode core to the ring, which was calculated by the formula $\alpha_{cr} = -10\lg P_r$. One can see from Fig. 3 that it strongly depends on a_2. For $a_2 > 27$ μm, the crosstalk attenuation α_{cr} may exceed 50 dB.

While calculating the crosstalk attenuation α_{rc} from the ring to the single-mode core, we approximated the distribution of the fields of the modes of the ring fibre by the distribution of the H_m modes of a planar fibre of thickness $a_3 - a_2$ [8] and determined the total normalised fraction of power P_c of these modes, which propagates in the single-mode fibre in the case of their uniform excitation. Fig. 4 shows the obtained dependence of $\alpha_{rc} = -10\lg P_c$ on a_2. For $a_2 > 20$ μm, we have $\alpha_{rc} > 60$ dB.

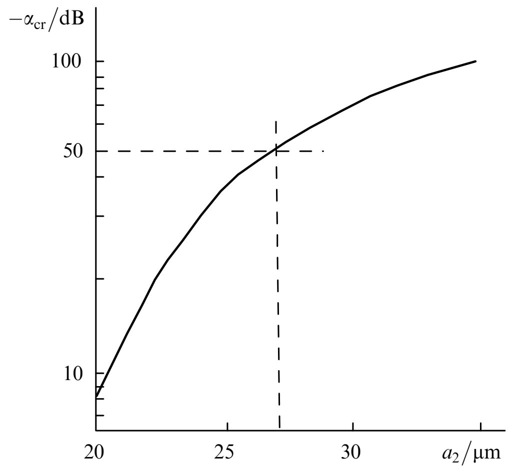


Figure 3. Calculated dependence of the crosstalk attenuation α_{cr} from the single-mode core to the ring waveguide on the ring radius a_2.

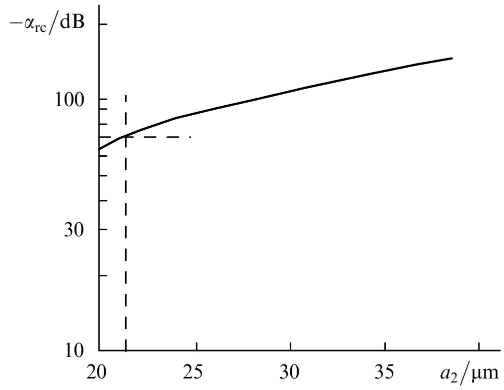


Figure 4. Calculated dependence of the crosstalk attenuation α_{rc} from the ring waveguide to the single-mode core on the ring radius a_2.

Thus, the numerical calculations show that a high optical isolation of the channels (exceeding 50 dB) can be achieved with an appropriate choice of the corresponding values of Δn and for the distance between the core and the inner radius of the ring higher than 20 μm.

3. Fabrication technology and the synthesis of the refractive index profile

We fabricated the preforms of fibres using the conventional MCVD technology of layer deposition inside the bearing quartz tube. A specific feature of the structure of the refractive index profile of real ring fibres is that a thick (~ 5–10 μm) protecting layer of pure SiO_2 should be produced between the ring and the material of the bearing quartz tube to eliminate the possible effect of the high amount of hydroxyl groups OH^- on the losses in the ring fibre. Fig. 5 shows a typical refractive index profile in the preform of fibre no. 801 with the refractive index differences $\Delta n_c = 0.018$ and $\Delta n_r = 0.011$ in the single-mode core and in the ring fibre, respectively.

When the fibre preform was pulled to fabricate the fibre, the diameter of the single-mode core was 4–5 μm, and the inner and outer diameters of the ring were 40 and 60 μm, respectively. The outer diameter of the fibres was 125 μm. Taking into account the results of numerical calculations,

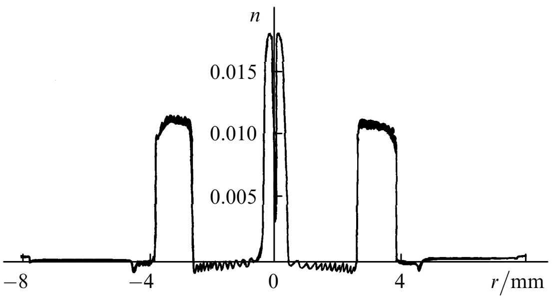


Figure 5. Typical refractive index profile in the preform of a two-channel concentric fibre.

we tried to make the rings of all fibres of the same (standard) size (40/60 μm). This provides splicing of the fibres and facilitates an analysis of optical losses by varying the main technological parameters of the concentric structure – the differences between the refractive indices Δn_c and Δn_r of the single-mode core and the ring and the SiO_2 cladding.

By setting the geometrical sizes, we varied only one technological parameter, the difference in refractive indices of the ring fibre Δn_r, in the limits 0.008 – 0.014, and maintained the corresponding difference Δn_c for the single-mode core at the level 0.018 ± 0.002. Thus, we created the difference of propagation constants for the ring modes and the single-mode core and provided the suppression of all possible effects of distributed coupling between the single-mode core and the ring.

This technology was used for preparing more than 100 km of fibres. Acrylate or elastic silicon rubber and varnish were applied as a secondary coating during drawing.

4. Dependence of losses on the parameters of profile and bends of fibres

In the fibres prepared by us, the core was a virtually conventional single-mode fibre with the cutoff wavelength of approximately 1.25 μm and low optical losses $\alpha_c \leqslant 1$ dB km^{-1} (see Table 1). The existence of a large value $\Delta n_c = 0.018$ in the single-mode core led to a certain increase in attenuation due to Rayleigh scattering and lowered the sensitivity of the losses to bends and microbends. The concentration of the HE_{11} mode field near the fibre axis should produce a favourable effect on the level of crosstalk between the core and the ring. There are no other specific features of the single-mode fibre in the concentric geometry. We will consider the possible effect of peculiarities in the fabrication technology on the losses in the single-mode core in connection with experiments on backward Rayleigh scattering.

From the standpoint of waveguide properties, a ring fibre is a special type of a fibre in which the optical axis is not the axis of maximum concentration of energy of light waves being channelled, as in the case of the HE_{11} mode of conventional fibres. In the ring fibre, there is no light transport by the HE_{11} mode along the geometrical axis and it rather represents a planar multimode fibre of thickness ~ 10 μm rolled into a light-guiding tube. As a result, we can expect a high sensitivity of the ring fibre to irregularities such as bends and microbends.

It should be noted that the waveguide theory as applied to fibres with a ring geometry does not provide the answer to the question concerning the minimum attainable optical losses in such a structure and does not permit a description of the dependences of losses on bends and microbends because of the complexity of the theoretical analysis. We deal here with the case when it is the experimental data that must provide answers to the questions formulated above, indicate the order of magnitude of the effects, and give values of parameters for calculations. It is important that the experiments should be made under appropriate conditions.

First, we measured the losses α_r in the ring core at the wavelength 1.3 μm for all the fibres fabricated by us. During pulling, fibres were wound on technological drums of radius $R = 16$ cm and then were rewound on the experimental coils of radii 8 and 10 cm under tensile forces $F_t \sim 50 - 100$ g applied for testing the strength of the fibre. It was noted above that the technologically varied parameter for fibres was the difference Δn_r in the refractive indices for the ring, but two additional variable parameters appeared during rewinding on the coils – the winding radius R and the tensile force F_t. In addition, the effect of tension on losses depended on whether the winding turns overlap irregularly or the fibres are placed layer by layer with a soft paper interlayer between the fibre layers.

Fig. 6 shows some experimental dependences (symbols) of the ring losses α_r on the winding radius R. In this case, Δn_r and F_t play the role of parameters. One can see that the losses α_r strongly depend on Δn_r and F_t both for a winding on the technological drums of radius $R = 16$ cm, and on the experimental coils with radii 8 and 10 cm. The largest losses $\alpha_r = 10 - 20$ dB km^{-1} on the coils are observed for fibres with small values of $\Delta n_r = 0.007 - 0.009$ for tensile stresses $F_t = 50 - 100$ g. Obviously, such high losses in the ring are unacceptable in practical applications and the spread in experimental points indicates the ambiguity of experimental data, complicating the analysis aimed at attaining minimal losses. Note that the optical quality of the initial materials was quite high, which is confirmed by relatively small ($\alpha_c <$ 1 dB km^{-1}) optical losses in the single-mode core fabricated in the same technological cycle with the ring fibre. The data presented in Fig. 6 indicate a strong effect of bends and microbends on the optical losses in the ring waveguide.

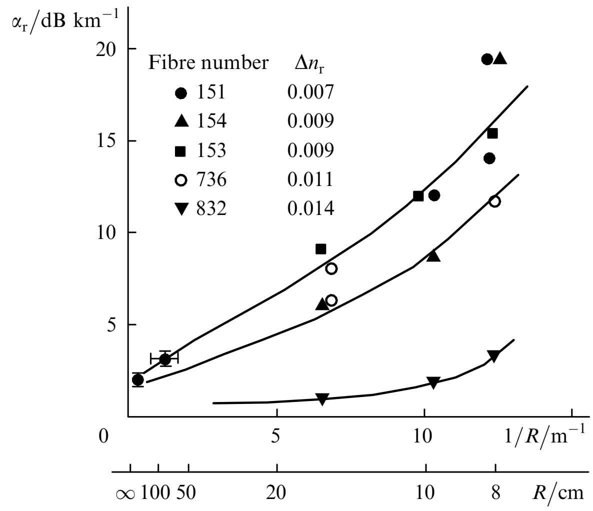


Figure 6. Experimental dependences of optical losses α_r in the ring waveguide (symbols) at a wavelength of 1.3 μm on the winding radius R for an uncontrollable (nonzero) tension.

The fibre no. 151 having a length of 1 km, which was found to be most sensitive to bends, was subjected to rewinding on a coil of radius $R = 1$ m under a small tensile stress $F_t \sim 10$ g and subsequently to unwinding and straightening under the laboratory conditions ($R \approx \infty$). In both cases, it was found that losses in the ring decreased sharply to $\alpha_r \approx 2 - 3$ dB km^{-1} (see Fig. 6), which confirms the assumption concerning the strong dependence of the ring losses on bends and microbends. For the fibre no. 832 with $\Delta n_r = 0.014$, it was found that the optical losses in the ring after the rewinding on a drum of radius $R = 16$ cm under a small tensile force $F_t = 10$ g amounted to 1 dB km^{-1}, which approximately coincides with the losses in the single-mode core. The rewinding of this fibre to experimental coils of radius 8 cm led to an increase in the ring losses to $2-3$ dB km^{-1}.

The data presented in Fig. 6 indicate that the ring losses may become as small as the losses in the single-mode core (~ 1 dB km^{-1}). Taking this into account, we studied the dependence of the ring losses α_r on Δn_r for all the fibres fabricated by us with substantially different values of Δn_r. In order to rule out any ambiguity in the results, which is very important in the present case, all fibres were rewound on a coil of radius $R = 16$ cm under the minimal tensile force ($F_t < 5$ g). A thin tissue interlayer was put between fibre layers. The results of measurements are presented in Fig. 7. One can see that the dependence $\alpha_r(\Delta n_r)$ demonstrates a virtually linear decrease in losses on bends upon increasing Δn_r up to 0.0140 ± 0.0005. For $\Delta n_r = 0.014$, the losses in the ring fibre attain the minimum value ($\alpha_r = 1$ dB km^{-1}) typical of the losses determined by the optical quality of the core material. In the straightened state, small ring losses can also be observed in fibres with $\Delta n_r = 0.010 - 0.013$. The main parameters of concentric fibres are presented in Table 1 and include the data for fibre nos 832, 865, and 866 for which the best results on attenuation in the ring were obtained.

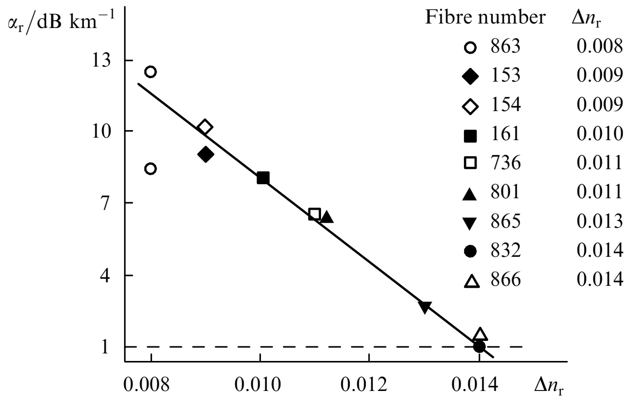


Figure 7. Experimental dependence of optical losses α_r in the ring on the refractive index difference Δn_r in the ring for $R = 16$ cm and $F_t < 5$ g.

Table 1. Basic parameters of concentric two-channel fibres wound with a small tension ($F_t < 5$ g) on a drum of radius $R = 16$ cm. Optical losses α_c and α_r and crosstalk attenuations α_{cr} and α_{rc} were measured at a wavelength of 1.3 μm.

Fibre number	Length /m	$\Delta n_c/\Delta n_r$	Optical losses/dB km^{-1}		Crosstalk attenuation/dB	
			α_c	α_r	α_{cr}	α_{rc}
801	3840	0.018/0.011	0.90	6.9	− 42	− 52
832	3100	0.016/0.014	0.94	1.0	− 45	− 55
865	4760	0.020/0.013	0.70	1.6	− 48	− 58
866	4140	0.016/0.014	0.81	1.4	− 49	− 57

Note: The error in the measurements of crosstalk attenuations α_{cr} and α_{rc} is 10 %.

5. Crosstalk attenuation in two-channel concentric fibres

Optical isolation of channels is one of the main parameters of two-channel fibres. The above theoretical analysis shows that we can expect a high optical isoaltion (above 50 dB) of the channels for two-channel concentric fibres with the geometry under study. This imposes a stringent requirement on the measurements of crosstalk losses α_{cr} and α_{rc}; namely, for the excitation of the single-mode core or the ring, the excitation level of the other channel must be $60-70$ dB lower in the optical power, which sets special limitations on the devices and methods of separate excitation of the channels.

Obviously, to excite the single-mode core, a single-mode fibre with exactly the same refractive index profile should be used; the core should be perfectly adjusted in the radial direction. The loss level in joining (splicing) of ~ 0.01 dB, which is usually regarded as admissible for splicing single-mode fibres, is completely unacceptable in this case because an optical noise at the level of -20 dB can appear during the excitation even at the input. Note that the experimental data on the crosstalk attenuation obtained in Refs [2, 6], where crosstalk between the channels of two-channel fibres was measured, usually were not less than -20 to -30 dB. For this reason, we have used in our work the excitation and measuring schemes presented in Fig. 8 for the reliable measurement of the crosstalk attenuation parameters α_{cr} and α_{rc}.

For measuring the crosstalk attenuation α_{cr} from the single-mode core to the ring, we removed the ring at the input end of the fibre over the length ~ 0.3 m by etching, retaining the single-mode core to provide the excitation of

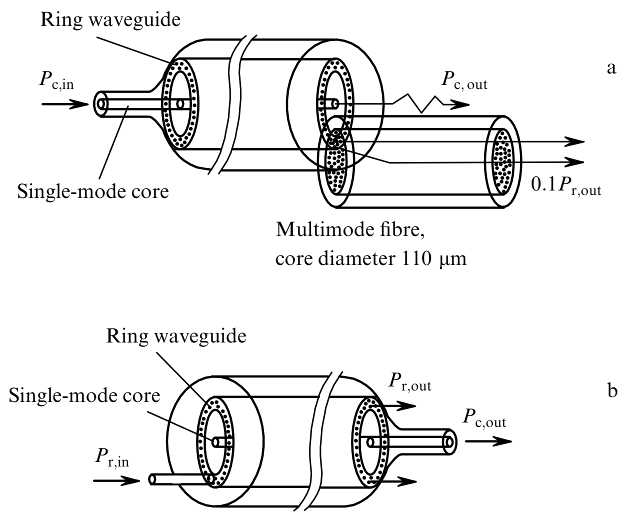


Figure 8. Excitation of the single-mode core and the measurement of crosstalk attenuation α_{cr} from the single-mode core to the ring waveguide (a) and excitation of the ring waveguide and the measurement of crosstalk attenuation α_{rc} from the ring waveguide to the single-mode core (b).

the single-mode core alone (Fig. 8a). Having removed the leaky and cladding modes, we ensured the optical isolation level for the excitation of the single-mode core at the input no less than 70 dB relative to the ring waveguide excitation.

We measured the optical signal power $P_{\rm r,out}$ at the ring output using an auxiliary segment of a multimode fibre of length ~ 1 m with the diameters of the core and the cladding of 110 and 125 μm, respectively. At the output edge, this segment was displaced from the optical axis of the two-channel fibre so that only 1/10 part of the output power $P_{\rm r,out}$ was extracted from the ring; in this case, the multimode fibre was perfectly optically isolated from the single-mode core. At the same time, this multimode fibre aligned with the two-channel fibre was used to measure the optical power $P_{\rm c,out}$ extracted from the single-mode channel. The crosstalk attenuation from the single-mode core to the ring was determined by the formula $\alpha_{\rm cr} = 10 \times \lg(P_{\rm r,out}/P_{\rm c,out})$. The measured values of $\alpha_{\rm cr}$ for the fibres under study are presented in Table 1.

We found that for the fibres under study, there exists a steady-state regime for the level of cross losses $\alpha_{\rm cr}$, which becomes stabilised for fibre lengths exceeding 0.5 km. The steady-state values of the parameter $\alpha_{\rm cr}$ for each fibre serve as its characteristic and indicate the dynamically equilibrium energy distribution over waveguide modes in both channels and a good optical isolation of the channels, exceeding 40 dB. The obtained values of the parameter $\alpha_{\rm cr} = -40\ldots-50$ dB are determined by the conditions of winding and the tensile force applied during winding on the coils. In our experiments, the crosstalk attenuation $\alpha_{\rm cr}$ was measured using the method described above for all fibres wound on a coil of radius $R = 16$ cm under a small tension $F_{\rm t} < 5$ g.

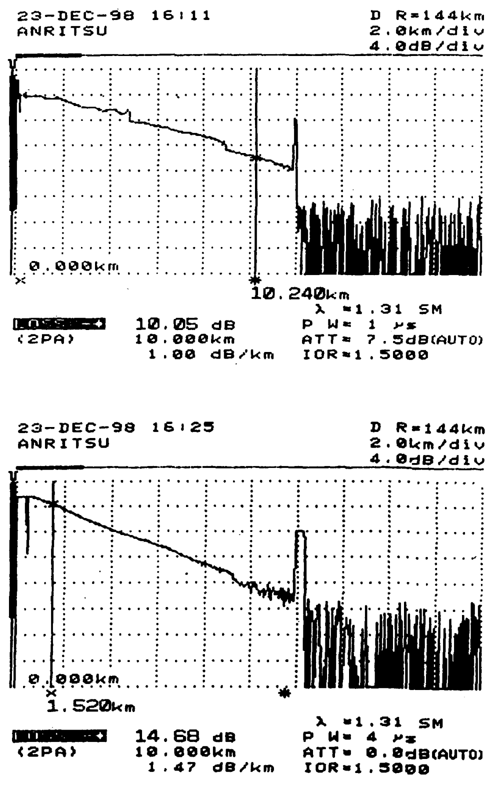
The optical scheme for measuring the crosstalk attenuation $\alpha_{\rm rc}$ from the ring to the single-mode core is shown in Fig. 8b. The ring was excited with the help of an auxiliary segment a single-mode fibre with a core diameter of 7 μm at a wavelength of 1.3 μm. The optical power $P_{\rm c,out}$ at the output of the single-mode core was also measured after the etching of the ring and the extraction of cladding and leaky modes. The experiments showed that the power $P_{\rm c,out}$ can be measured with an error of about 10 % with the help of a selected single-mode fibre segment with a thin cladding (in order to prevent the trapping of radiation from the ring output). The radiation power $P_{\rm r,out}$ at the output of the ring fibre was measured using a segment of a multimode fibre with a core of diameter 110 μm adjacent coaxially with the output of the two-channel circular fibre. The crosstalk attenuation from the ring to the single-mode core was determined from the formula $\alpha_{\rm rc} = 10\lg(P_{\rm c,out}/P_{\rm r,out})$. The obtained values of $\alpha_{\rm rc}$ range from -50 to -60 dB (see Table 1) and indicate a high optical isolation of the channels.

The crosstalk attenuation $\alpha_{\rm rc}$ is approximately an order of magnitude higher than $\alpha_{\rm cr}$. This indicates that the field of the HE_{11} mode of the single-mode fibre leaking at bends in the fibre wound on a coil is partially trapped by the multimode ring waveguide. The back transfer of radiation from the multimode waveguide fibre to the core is hampered due to the substantially different structures of the fields of the waveguide modes of the ring and of the single-mode fibre. Because of a considerable difference between the refractive indices of the core and the ring, the propagation constants of waveguiding modes are also different and there is no appreciable effect of the distributed coupling between the channels, which could considerably reduce the crosstalk attenuation between them.

6. OTDR experiments and attenuation distribution in a 12-km long fibre line on two-channel concentric fibres

To confirm additionally the absence of a distributed coupling between the channels for large lengths of fibre lines and to verify the efficiency of the splicing of concentric two-channel fibres, we studied the Rayleigh backscattering and the distribution of optical losses over the fibre line length. For this purpose, we constructed a fibre line of length 12 km from fibre nos 832, 865, and 866. Owing to the standard geometrical sizes of two-channel concentric fibres, we spliced them with small optical losses using the US-126SM mechanical splicers applied for splicing of conventional single-mode fibres with an outer diameter of 125 μm.

Rayleigh backscattering signals from the single-mode core were recorded with a standard MW910C (Anritsu) reflectometer operating at a wavelength of 1.31 μm. Fig. 9a shows the recording of the OTDR signal from the single-mode core for an optical fibre line of length 12 km. Two steps corresponding to the fibre splicing with losses approximately equal to 1 dB are observed in the curve. The average attenuation on a segment of length 10 km indicated by markers in Fig. 9a was 1 dB km^{-1}. Elevated losses in the regions of splicing are due to the fact that the refractive index profile for the single-mode core and the values of $\Delta n_{\rm c}$



a

b

Figure 9. Distribution of backscattering (OTDR) signals in a fibre line with two-channel concentric fibres of length 12 km for a single-mode core (a) and ring fibre (b) for an average attenuation of 1 db km^{-1} in the single-mode core and 1.47 dB km^{-1} in the ring waveguide.

at the segments being spliced were somewhat different (see Table 1). In addition, the outer diameter of fibres (125 μm) was maintained to within ±1 μm, which was also manifested in the radial mismatching of single-mode cores and in the losses in the splicing regions. The first segment of the fibre line in fibre no. 865 had the elevated value $\Delta n_c \approx 0.020$. Small variations in the OTDR signal over the length of this fibre related fluctuations in the GeO_2 content in the core and to some variations in its diameter can be seen. On the whole, the OTDR signal, taking into account the peculiarities of the single-mode core indicated above, is quite regular. These data also indicate the absence of a distributed coupling between the single-mode and ring channels, which could lead to a strong redistribution of the power between the channels over the length of 12 km.

Using an individual three-coordinate table, we excited the end of a ring waveguide through a single-mode fibre emerging from the MW910C reflectometer. Due to considerable losses upon the extraction of the backward Rayleigh scattering signal, we lost about 10 dB from the dynamic range of the reflectometer, however, the OTDR signal from the ring waveguide was reliably observed over the entire 12 km (see Fig. 9b). One can see that ring fibres are matched much better than single-mode fibres and the splicing losses do not exceed 0.3 dB. This is due to the fact that the spread in the outer diameter of fibres of ±1 μm affected the area overlap in the cross section of ring cores to a smaller extent.

The regular form of the dependence of the OTDR signal over the entire length of 12 km also indicates the absence of a distributed coupling between the channels. The average attenuation in the ring fibre in the line was 1.47 dB km^{-1}.

7. Conclusions

Based on the theoretical analysis and experimental studies, new two-channel concentric fibres with a broadband single-mode fibre channel and an additional multimode ring waveguide, intended for two-channel and duplex communications, as well as for some other special applications, are developed. The effect of regular bends and microbends on the attenuation in the ring is analysed, the optimal construction is determined, and the parameters of two-channel fibres with losses in the single-mode fibre not exceeding 1 dB km^{-1} are determined (the losses in the ring core in the fibre wound on coils do not exceed 1.5 dB km^{-1}, while the losses in the straightened state are less than 1 dB km^{-1}). It is shown that in fibres with optimised parameters of the refractive index profile, the optical isolation of the channels may exceed 40 dB, which permits many special and unique applications of such fibres.

Coherent laser radiation can be transmitted independently through the single-mode fibre channel simultaneously with radiation propagating along the ring fibre. The fibres developed here can be used for designing multifunctional fibre-optics sensors of the interferometric type as well as amplitude sensors operating on incoherent light fluxes in a ring fibre. The outer diameter (125 μm) of the fibres described here coincides with the diameter of conventional communication fibres; consequently, two-channel fibres can be spliced into long lines with the help of standard technological approaches and devices. The separate and independent excitation of the single-mode and ring channels necessitates the development of special input – output fibre devices – directional couplers with appropriate parameters and losses. This is an independent technological problem and is the subject of a separate study.

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