Simulation and analysis of mode staff excitation during "O"-band optical signal launching to graded multimode fiber with large central defect of refractive index profile via standard singlemode fiber

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ABSTRACT

In article results of the theoretical analysis of power rescheduling of the optical signal, launched by a coherent light source in "O" - band, terminated by standard singlemode optical fiber ITU-T G.652, between the guided modes of silica graded multimode fibers with large technological defect of a refractive index profile in the core center are presented.

Keywords: few-mode signal propagation, differential mode delay, multimode optical fiber, graded refractive index profile, technological profile defect, MCVD, high-order mode excitation, radial offset

1. INTRODUCTION

Actually today multimode optical fibers (MMF) are a basis of compact multiport infocommunication networks Such fiber optic lines differ in short distance (formally to 2 km, in practice – hundreds, and in some cases – even tens of meters) in case of high transmission bitrates at the same time [1–3].

Proceeding to multigigabit bitrates demands application of coherent light sources in optical modules of the active equipment of such networks[1, 3–7]. Use of the last in combination with MMF forms the few-mode regime. At the same time optical signal is transmitted by limited mode content. A key factor of optical pulse distortions in the few-mode regime is the differential mode delay (DMD)[1, 3–7], caused, on the one hand, by conditions of signal input from a laser output in MMF and lightguide refractive index profile variations from an optimal graded form with another hand. So first generation quartz MMF with technological defects of a refractive index profile in the large dip or peak form in the core center, for which strong DMD effect and, respectively, unacceptably low bandwidth value in the few-mode regime is characteristic, have been replaced by new generation of quartz graded MMF (category OM3 … OM4), optimized for operation with laser sources[4, 5, 7] on multigigabit data transmission networks. As a result from the view point of the application on infocommunication networks this type of graded MMF with large technological defect of refractive index profile in the core center is not demanded today and is practically not delivered on the cable industry.

At the same time, potential opportunities of a developed alternative method for registration of external influences were shown in earlier published articles[8–13]. This method is based on the few-mode effects by optical signal transmission generated by a coherent light source on MMF unlike the classical approaches realized in commercial fiber optical sensor systems and the vast majority of proprietary decisions[14–17].

Excitement of short optical fiber lengths from several centimeters and even less to meter and more with increased, in comparison with standard singlemode fiber (SMF), core diameter, using laser, including via matching SM-lightguide, is

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rather widely used at realization various interferometric schemes for example[15, 18–24]. Some publications is devoted to the application of the fiber Bragg gratings on MMF lengths and effects for various fiber optical sensors schemes – vibration, temperature, deformation and etc[25–29]. Here it should be noted that the vast majority of the submitted schemes are focused only on the analysis of a spectral response of fiber optic structure with inclusion of MMF length at excitement by a coherent light source, that, as it has been noted above, corresponds to the few-mode regime under such conditions. In this sense it is advisable to allocate the publications, focused on registration and processing of the monitoring pulse and/or its response when passing extended MMF lengths by optical time domain reflectometry methods (actually, today for these applications MMF are forced out by SMF[30, 31]) and the analysis of speckle images[30, 32–34], in separate group.

Unlike the known decisions, the proposed approach of registration of external influences is based on the analysis of response change of the few-mode optical small duration signal excited in a sensor (extended MMF) by a coherent light source. Comparison of the "base" and "current" pulse form detected at the output of the tested MMF is carried out at monitoring. Because of the enclosed external local or distributed influence (for example, mechanical or temperature), new micro and macrobends appear on MMF sensor. It inevitably changes the interaction and mixture processes for mode components. In turn, it significantly influences change of the pulse response form distorted at the expense of DMD. Therefore it is offered to use MMF with strong DMD effect in the few-mode regime as a sensitive element for this decision.

The analysis of the results, received during previously carried out theoretical and experimental researches, has shown that the strongest DMD effect corresponds to first generation MMF of OM1 and OM2 categories[35–37]. At the same time the graded refractive index profile of such fibers differs in existence of characteristic technological defect in the core center in the large dip or, on the contrary, peak form and also presence of strong refractive index fluctuations[36]. It has allowed to execute selection, grouping and preparation of the lightguides preforms, which made on MCVD technology with the described large technological defect of a graded refractive index profile, as a result of the analysis and comparison of measurement protocols which is carried out on the basis of Research and Technological Institute of Optical Materials All-Russia Scientific Center "S.I. Vavilov State Optical Institute" laboratory. One of examples (preform №A4, distance of 250 mm) with a dip in the core center is presented on Figure 1.

Then the delivery lengths drawing of silica MMF 50/125 with specified dip or peak in the core center about 2 km long with the subsequent bobbin rewinding on 500 m everyone was realized from these selected preforms. Further repeated measurements of refractive index profiles of the received industrial MMF samples are taken. The protocol of this characteristic of fiber №A4 at distance of 1000 m is provided on Figure 2.

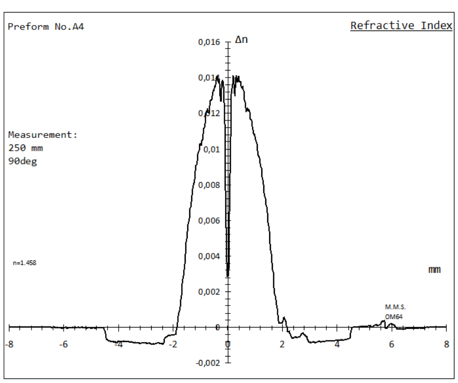
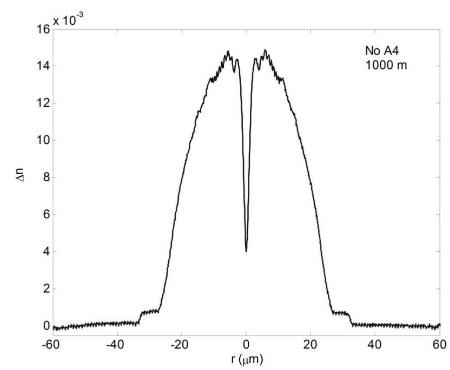


Figure 1. Graded refractive index profile of silica preform (sample №A4, distance from the beginning of a preform of 250 mm) with a dip in the core center.



Fugure 2. Graded refractive index profile for MMF 50/125 (sample №A4, distance from the beginning of 1000 m) with a dip in the core center.

As it was noted above, the second factor determining DMD effect are conditions of signal input from a laser output in a lightguide core in addition to MMF parameters[1, 3–7, 38, 39]. It is also confirmed by the existing measurement standards for effective modal bandwidth of MMF in the few-mode regime – in particular, TIA-455-220-A/FOTP-220 and IEC 60793-2-10 which are based on the analysis of so-called "map" or "profile" of DMD. "Map" or "profile" of DMD represents the pulse responses range of the few-mode optical signal registered at the output of the tested MMF and constructed as a result of precision scanning of an input end of MMF by a coherent light source with the use of the matching SMF. Thus, it is supposed that, proceeding from features of a graded refractive index profile, it is possible to pick up such input conditions in case of which the strongest DMD effect will be observed. At the same time, unlike information signal transmission via MMF, on the contrary this regime with the strengthened DMD effect is optimum from the view point of the proposed alternative approach of registration of external influences based on the few-mode effects.

In article results of the theoretical analysis of power rescheduling of the optical signal, launched by a coherent light source in "O" - band, terminated by standard singlemode optical fiber ITU-T G.652, between the guided modes of silica graded multimode fibers with large technological defect of a refractive index profile in the core center are presented. Source type – SM Fabry-Perot laser diode (operation wavelength λ=1310) and the matching lightguide – standard singlemode fiber ITU-T G.652 were selected proceeding from a hardware components of the DMD analyzer (R2D2) of few-mode technologies of fiber optics and photonics laboratory of department of communication lines PSUTI[8–13, 35, 37]. It is directly used for comparing of a "base" and "current" pulse shape in case of registration of the external local or distributed influences on MMF sensor.

2. ALGORITHM OF THE ANALYSIS OF OPTICAL SIGNAL INPUT FROM A LASER OUTPUT VIA MATCHING SM LIGHTGUIDE IN GRADED MULTIMODE OPTICAL FIBER

Generally the mathematical description of MMF excitement by some light source can be consolidated to the analysis of a splice "matching lightguide – MMF". Such approach, in particular, allows to simulate typical schemes for optical radiation input in optical fibers of interconnecting links of different cable systems at connection of sources of commercial optical modules of fiber-optical transmission lines. For example, some modern transceivers, including SFP modules (Small Form-factor Pluggable – compact transceivers), assume signal input from an output of a light-emitting laser surface directly in patchcord optical fiber pasted in the optical connector of the corresponding type via the alignment plug. Further the second end of an optical patchcord via the optical socket of the switch (a patch panel, an optical terminal box) is connected to the set cable fiber, which terminated by using appropriate technology.

The following input scheme is quite often used. Not terminated end of the pigtail lightguide via some matching device (for example, a lens) is pasted on the light-emitting laser surface. Another end, respectively, is terminated by the optical connector brought from the inside to the optical socket of a transceiver front panel. As a result the line fiber or the optical patchcord for the subsequent switching on an optical terminal box is connected to the transceiving module via the specified optical socket from outside. Such scheme is applied also in measuring technique. In particular, the mentioned DMD analyzer (R2D2) is equipped with the SM laser diode, which terminated by standard singlemode fiber (SSF) ITU-T G.652 brought from the inside to the optical socket of a front panel of the device[35]. Thus, conditionally uncontrolled signal input is carried out by simple connection of MM pigtail, which spliced to the tested MMF, to a light source via the specified socket on a front panel. While specialized conditions of optical laser emission input (aligned or input with radial offset) can be realized by splicing not terminated SM pigtail end connected to the optical socket from outside of the front R2D2 panel to the tested MMF by means of the appropriate program.

In this article the analysis of the power rescheduling of the optical signal in "O" - band entered from an output of SM LD in graded MMF via the matching lightguide SSF is proposed to be realized by calculation of mode coupling coefficients on a splice of the specified fibers. This approach still remains today to one of the most known and simple methods of the analysis of optical emission transition from one mode to another. This method is widely applied at estimation of the insertion losses and reflection coefficient on the splice of an optical fibers of identical configuration with variation of separate technological parameters[40–43], at modeling and researching of influence of signal input conditions on excitement of optical waveguides[44–47], including at modeling of optical signal distribution via optical fiber in the few-mode regime[6, 38, 39, 48, 49].

Generally the mode coupling coefficient for mode p, exciting mode q, is defined by overlap integral of interacting mode field which in scalar statement for cylindrical coordinate system has the following appearance[6, 3–49]:

$$\eta_{pq} = \frac{\left| \int\limits_0^{\infty} \int\limits_0^{2\pi} F_p F_q r dr d\varphi \right|^2}{\int\limits_0^{\infty} \int\limits_0^{2\pi} \left| F_p \right|^2 r dr d\varphi \int\limits_0^{\infty} \int\limits_0^{2\pi} \left| F_q \right|^2 r dr d\varphi}, \qquad (1)$$

where F_p и F_q – radial field distributions for the interacting modes LP_{lm} – launched from a source output mode p and excited in optical fiber mode q.

For passage to high order modes, which field structure has more difficult character unlike the fundamental mode LP_{01}, it is proposed to use the known approximating expression corresponding to the exact decision of the scalar wave equation for optical fiber with an ideal unlimited parabolic refractive index profile, which within Gaussian approximation has the following appearance[47]:

$$F_m^{(l)}(R) = \left(\frac{R}{R_0}\right)^l L_{m-1}^{(l)}\left(\frac{R^2}{R_0^2}\right)\exp\left(\frac{-R^2}{2R_0^2}\right), \tag{2}$$

where l and m – azimuthal and radial orders of mode LP_{lm}, accordingly; $R = r/a$ – normalized radial coordinate; r – radial coordinate; a – core radius; $R_0 = \rho_0 / a$ – normalized mode field radius; ρ_0 – mode field radius; $L_{m-1}^{(l)}$ – Laguerre polynomial.

There are well known, based on the classical Gaussian approximation[47] and his various modifications[50–56] decisions, assuming representation of a refractive index profile of the researched optical fiber by only one or sets of simple smooth exponential functions that doesn't correspond to real industrial graded optical fibers[36, 57, 58]. In this article it is proposed to use the offered earlier extension of modified Gaussian approximation (EMGA)[59, 60] for calculation of spectral characteristics of dispersive parameters of the arbitrary order guided mode propagating in the weakly-guiding optical fibers with arbitrary axially symmetric refractive index profile. This method is based on a combination of Gaussian approximation method[47] modified for calculation of multimode optical fibers[59] and a stratification method[57]. Here the weakly guiding fiber lightguide with arbitrary axially symmetric refractive index profile and one external continuous cladding is considered as the weakly guiding fiber lightguide with a multilayered refractive index profile presented in the fiber core as finite number of layers N within which the refractive index remain to constant. As result the disaggregated reproduction of a refractive index profile of the researched optical fiber is provided at assignment of initial data that significantly reduces calculation errors[61]. Moreover, the described approach provides a possibility of passage to rather bulky, but analytical expressions for overlap integral (1) taking into account (2) in the form of the finite enclosed sums, which are given in earlier published article[60].

For passage from equivalent mode field radiuses, as a result of calculation on the basis of EMGA, to actual, it is proposed to use a well-known integrated form of a Petermann-I formula for the mode field radius in the near field[62]. After corresponding transformations and substitution of the approximating expression for radial distribution of the mode field (2) it is given to an analytical formula which conclusion is in detail stated in earlier published paper[63]:

$$\mathrm{MFR}_{\mathrm{NF}} = 2R_0\sqrt{2}\cdot\left[\frac{(m-1)!}{(l+m-1)!}\times\sum_{q=0}^{2m-2} D_q\,(l+q+1)!\right]^{\frac{1}{2}}, \tag{3}$$

where

$$D_q = \sum_{p=\max(0,q-m+1)}^{\min(q,m-1)} b_p^{(l,m-1)} b_{q-p}^{(l,m-1)},$$

$b_p^{(l,m)}$ – corresponding coefficients of exponential series of a formula of obvious expression for Laguerre polynomial $L_m^{(l)}(x)$[64]:

$$L_m^{(l)}(x) = \sum_{q=0}^{m} b_q^{(l,m)} x^q;$$

$$b_q^{(l,m)} = (-1)^q \frac{(l+m)!}{(l+q)!\,(m-q)!\,q!}.$$

Thus, the method of mode coupling coefficients calculation for modes, propagating from an output of the matching fiber lightguide to investigated MMF sensor, includes the following steps. Previously the refractive index profile and basic geometrical parameters of the tested MMF are set. Further calculation of equivalent mode field radiuses is performed by EMGA. Then passage from equivalent mode field radiuses to the actual values with use of expression for Petermann-I formula (3) is carried out. Then for the estimation of mode coupling coefficient substitution of the obtained values of mode field radiuses of the corresponding order for the matching lightguide and MMF sensor is carried out in a formula (1) which is written down in an analytical form for strictly coaxial splice or splice with the precision radial, angular and/or radial offset[60].

3. RESULTS OF ANALYSIS FOR A SPLICE OF STANDARD SMF AND GRADED MMF WITH LARGE DEFECT OF A REFRACTIVE INDEX PROFILE IN THE CORE CENTER

As it has been noted above, in this paper it is proposed to consider input of an optical signal in tested MMF which refractive index profile is presented on Figure 2, from an SM LD output generating an optical signal in the central area of "O" - band (λ=1310 nm) via matching lightguide (standard SMF ITU-T G.652)[1].

Measurements of SMF samples of different ITU-T recommendations such as G.652 Corning® SMF-28e™ (second half of the 2000th) which were used as the matching lightguides in DMD research stated in paper[35] were also carried out within the publications[36, 58], devoted to a research of defects of graded refractive index profiles of industrial MMF. So, on Figure 3 the refractive index profile of SMF fiber which was reproduced further on the basis of measurement data is shown. The database describing a profile on an interval from the core center to boundary core/cladding $r \in [0; a]$ contains 76 refractive index values n.

As it is well visible from Figure 3, the real profile rather strongly differs from idealized step. There are not only local fluctuations of refractive index, but also defect at the core center in the dip form. At the same time the profile form has smoothed character. Radial coordinate of a half a profile height $n_{max}/2$ makes 4.08 microns that doesn't contradict the specification[1] and, generally, is positioned in as core radius. However value of radial coordinate for boundary core/cladding reaches already 6.65 microns, as it is proposed to consider as the actual core radius value of the researched SSF.

Further calculation of mode transmission parameters of the considered SSF in the wavelength range λ=800…1350 nm was carried out by the strict numerical mixed finite element method (MFEM)[61] and approximate method EMGA[59]. The analysis and comparison of the obtained results showed that not only the fundamental mode LP_{01}, but also mode LP_{11}, which becomes leaking at λ>1325 nm, satisfy a cut-off condition[47, 57] in the area λ=1300±10 nm. The subsequent calculation of industrial standard singlemode fibers also showed similar results. The spectral characteristics of a normalized propagation constant of the guided modes LP_{01} and LP_{11} calculated by MFEM and EMGA for SSF (Figure 3) are given on Figure 4.

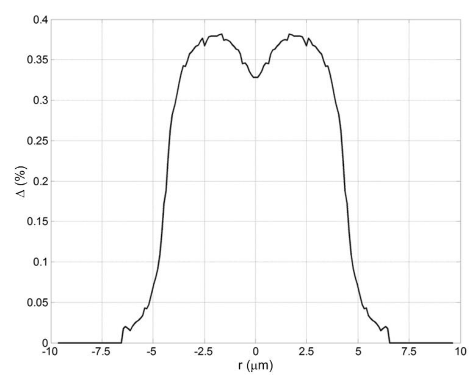


Figure 3. «Step» refractive index profile of industrial SMF ITU-T G.652.

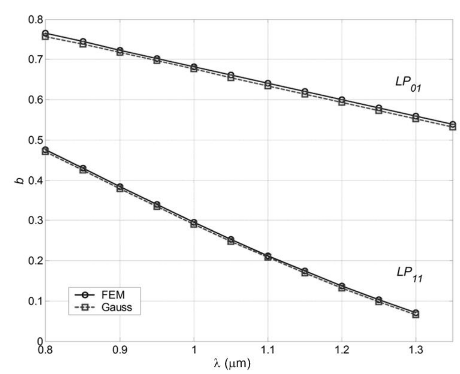


Figure 4. Spectral characteristics of a normalized propagation constant b of the guided modes LP_{01} and LP_{11} calculated by MFEM and EMGA.

Despite the small core radius and, respectively, rather small normalized frequency V=5.2…5.3, the estimation error for the normalized propagation constant b didn't exceed 1.5% for fundamental mode LP_{01} and 5% for mode LP_{11}, and estimation error for propagation constant β – 0.003% and 0.014% respectively in all researched wavelength range. Thus, at simulation of a SSF/MMF splice or excitation of MMF by the SM LD via the matching lightguide SSF, it is expedient to consider a possibility of mode input for LP_{11} in addition to fundamental mode LP_{01}.

Further calculation of mode transmission parameters for MMF 50/125 (Figure 2) was carried out by EMGA. So, 46 guided modes (l=12 azimuthal order and m = 6 radial order inclusively) satisfy a cut-off condition at simultaneous optical confinement factor $P_{co}\geq 0,5$ on λ=1310 nm (Figure 5).

At the first step it is proposed to consider input of an optical signal from an output of SM LD operating on λ=1310 nm via the matching lightguide SSF, supporting propagation of the fundamental mode LP_{01} and the high order mode LP_{11}, to an fiber end of researched MMF with the set precision radial offset.

Results of calculation of power rescheduling between the guided modes of MMF as the diagram of the normalized mode amplitudes are given on Figure 6. The value range of radial offset d=0…20 microns was researched. It was supposed that the specified modes LP_{01} and LP_{11} with equal amplitudes are launched from an output of matching SMF. The guided modes of the excited MMF with azimuthal order l=0 and l=1 were considered because according to paper[40] and the monograph[47] at the aligned input (d=0) and radial offset the power of the launched modes almost completely is passed to modes with identical azimuthal order, and coupling between modes with the relatively equal l is negligible: mode coupling coefficients make less than 10^{-10}.

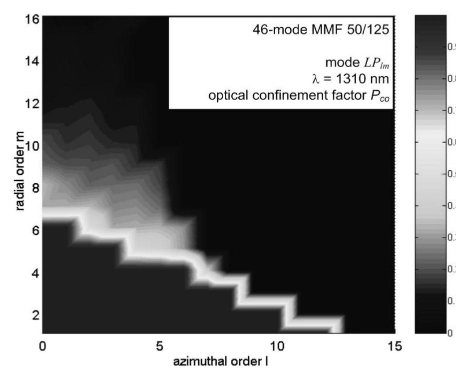


Figure 5. Distribution diagramm for optical confinement factor values on azimuthal and radial mode orders.

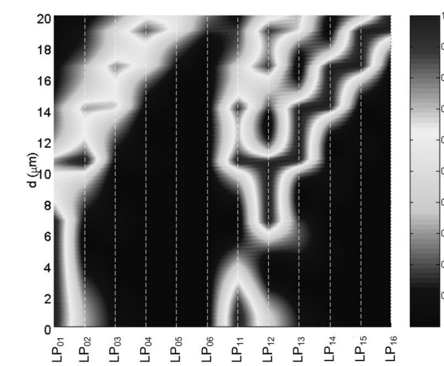
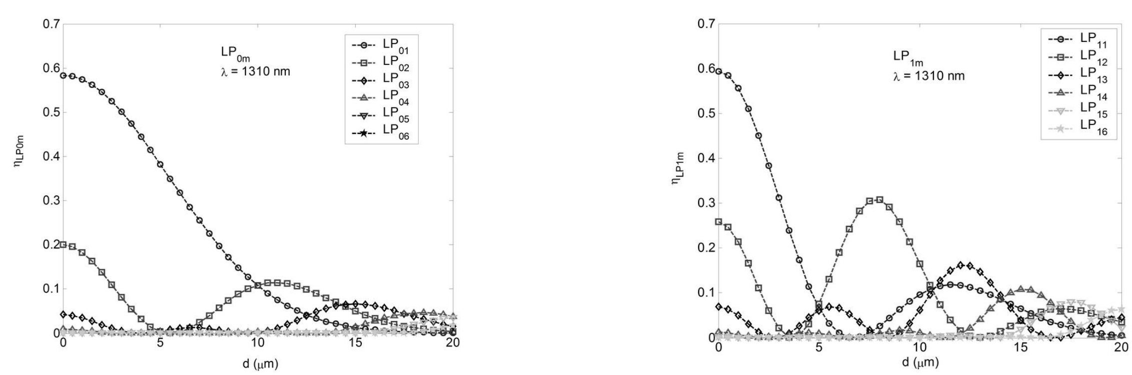


Figure 6. Distribution diagramm for normalized mode amplitudes of the excited modes of the researched MMF at input of the fundamental mode LP_{01} and the high order mode LP_{11} with equal power from SM LD output (λ=1310 nm) via SMF with the set precision radial offset.



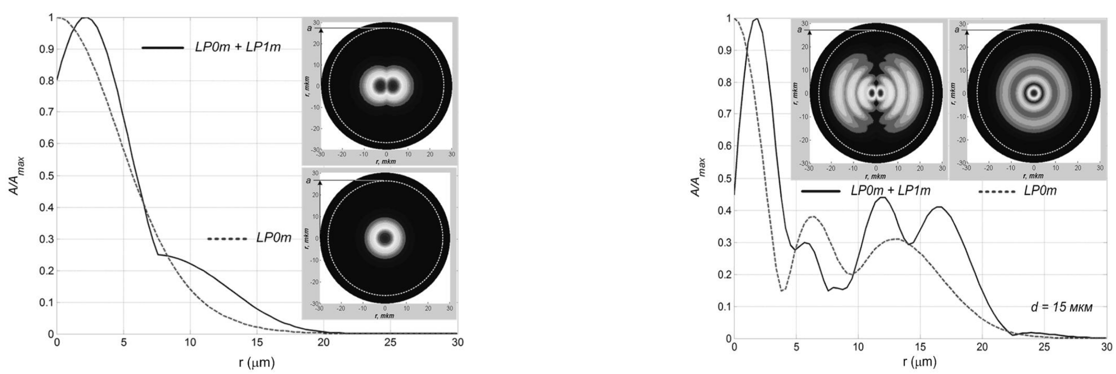
(a) (b)

Figure 7. Mode coupling coefficients on a splice SMF/MMF depending on the radial offset d: (a) launched fundamental mode LP_{01} and excited modes LP_{0m}; (b) launched high order mode LP_{11} and excited modes LP_{1m}.

On Figure 7 curves of mode coupling coefficients of the fundamental mode LP_{01} and modes LP_{0m} (Figure 7 (a)), and, respectively, mode LP_{11} and modes LP_{1m} (Figure 7(b)) on a splice of researched standard SMF and MMF depending on the radial offset *d* are presented. The analysis of the results shows that for these samples of optical fibers rather uniform excitement of the modes LP_{0m} and LP_{1m} is reached at the radial offset d>14 microns. It will be coordinated with recommendations of the specification 1000Base-LX of the IEEE 802.3z standard which regulates signal input from SM LD output (λ=1310 nm) via matching patchcord MCP providing radial offset 10…16 microns[1–3, 6]. On Figure 8 envelope superposition curves for the mode fields of the single-mode and two-mode signals excited in multimode optical fiber via SMF at the aligned input (Figure 8 (a)) and radial offset *d*=15 micron (Figure 8 (b)) are presented.

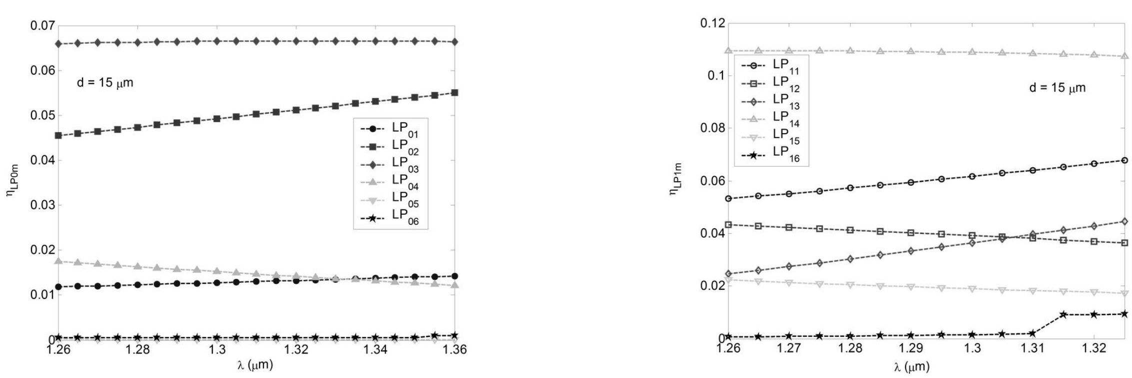
At the aligned input the main signal power of modes LP_{01} and LP_{11} is passed to modes of the same order and also partially to guided modes of the nearest radial orders – LP_{02}, LP_{12} and LP_{03}, LP_{13}, respectively. Here the amplitude variation between the specified components reaches values 50…60%. For the considered samples of matching SMF and MMF neighborhoods of local value of a radial offset *d*=5 micron for modes LP_{0m} and *d*=3.5 micron for modes LP_{1m} are of separate interest. In the specified areas, despite the general lowering of transmission coefficients of the launched modes LP_{0m} and LP_{1m} twice, almost complete suppression of high radial order modes is watched.

Results of calculation of spectral dependences of mode coupling coefficients for LP_{01} – LP_{0m} modes (Figure 9 (a)), and LP_{11} – LP_{1m} modes (Figure 9 (b)), respectively, in "O" - band at the strong set precision radial offset *d*=15 micron are presented on Figure 9. Similarly, results of calculation of spectral dependences of mode coupling coefficients for LP_{01} – LP_{0m} at the aligned input (Figure 10 (a)) and with radial offset 7.5 microns (Figure 10(b)) are presented on Figure 10. The analysis of the results shows that the essential variation of amplitudes of the excited modes remain in all researched spectral wavelength "O" - band at the aligned input and small radial offset.



(a) (b)

Figure 8. Envelope superposition curves for guided modes of MMF, excited: (a) at the aligned input of the two-mode (LP_{01} + LP_{11}) and singlemode (LP_{01}) optical signal via matching SMF; (b) at the radial offset *d*=15 micron (λ=1310 nm).



(a) (b)

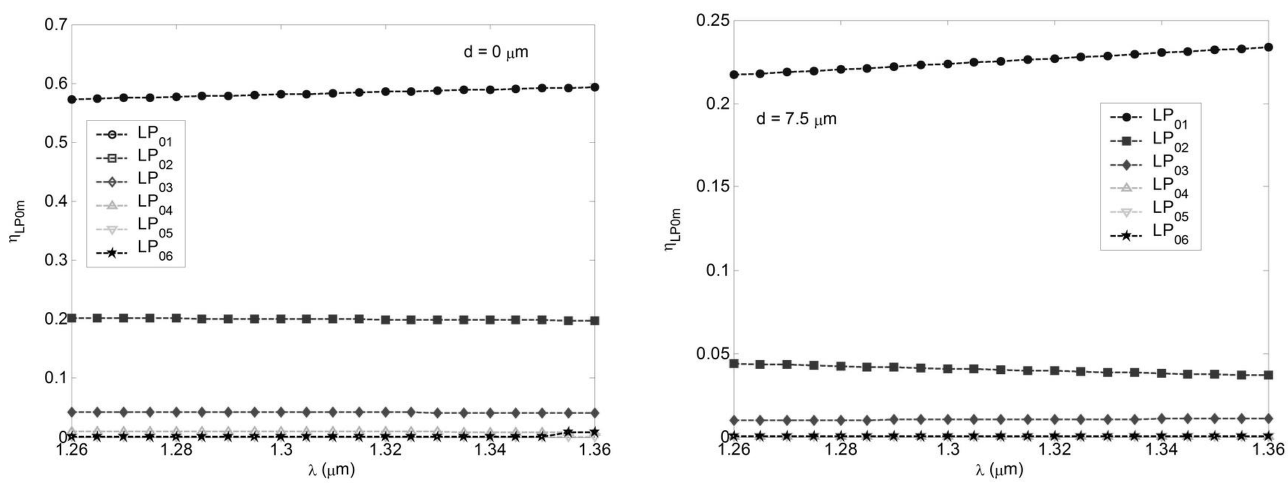
Figure 9. Spectral dependences of mode coupling coefficients on a splice SMF/MMF at the set radial offset *d*=15 micron: (a) launched fundamental mode LP_{01} and excited modes LP_{0m}; (b) launched high order mode LP_{11} and excited modes LP_{1m}.

Results of calculation of power rescheduling between the guided modes of MMF as the diagram of the normalized mode amplitudes are given on Figure 11. The small angular offset range θ=0…5.5^o, corresponding to standard fiber optical connectors[38, 39], was researched. Here it was too supposed that the specified modes LP_{01} and LP_{11} launch to MMF from an output of matching SMF with equal amplitudes.

Envelope superposition curves for the mode fields of the single-mode and two-mode signals excited in multimode optical fiber via SMF at the angular offset θ=5^o are presented on Figure 12.

According to the results, intermodal coupling including unequal azimuthal orders is characteristic for similar connections. At the rather small angular offset 0≤θ<2^o the main power of the launched modes LP_{01} and LP_{11} is passed to modes of the same orders, and residual part is rescheduled between zero and first azimuthal order modes. With increase in θ coupling between not only nearest, but also high azimuthal order modes amplifies. So, at the θ=5.5^o there are modes which normalized amplitude makes more than 0.1, up to azimuthal order *l*=4 inclusively.

The summary diagram of normalized mode amplitudes of the excited modes of the researched MMF at the input of the equal power fundamental mode LP_{01} and the high order mode LP_{11} from SM LD output via SMF at the fixed angular offset θ=5^o and the set optical carrier λ in "O" - band (1260 nm, 1285 nm, 1310 nm, 1330 nm and 1360 nm) is presented on Figure 13. According to the results of calculation, the mode LP_{11}, launched via the matching SMF, ceases to meet cut-off conditions at the passage to upper boundary of "O" - band, that for the set angular offset θ=5^o restricts the excited composition of the guided modes for which the normalized amplitude makes at least 0.1 to azimuthal order l=3 inclusively.



(a) (b)

Figure 10. Spectral dependences of mode coupling coefficients for launched fundamental mode LP_{01} and excited modes LP_{0m} on a splice SMF/MMF at the set radial offset: (a) *d*=0 micron; (b) *d*=7.5 micron.

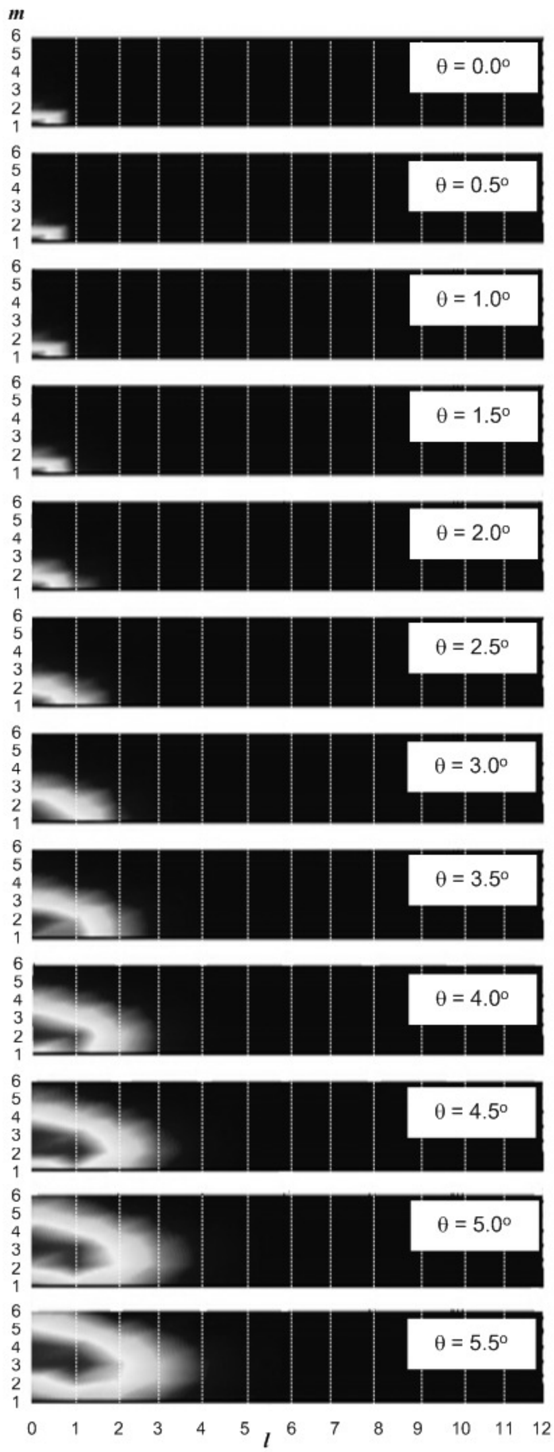


Figure 11. Diagram of the normalized mode amplitudes for excited modes of researched MMF at the launching of fundamental mode LP_{01} and high order mode LP_{11} with equal power from output SM LD (λ=1310 нм) via SMF with the set precision angular offset θ.

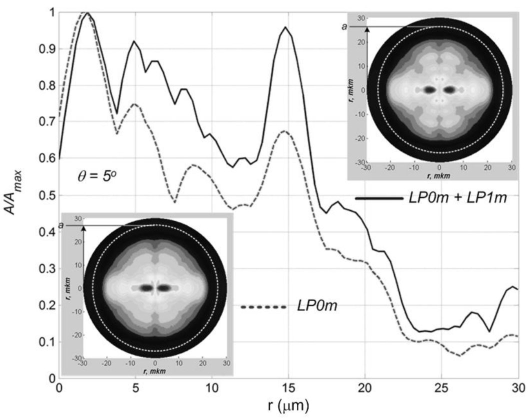


Figure 12. Envelope superposition curves for guided modes of MMF, excited at the angular input θ=5° (λ=1310 nm) of the two-mode (LP_{01} + LP_{11}) and singlemode (LP_{01}) optical signal via matching SMF.

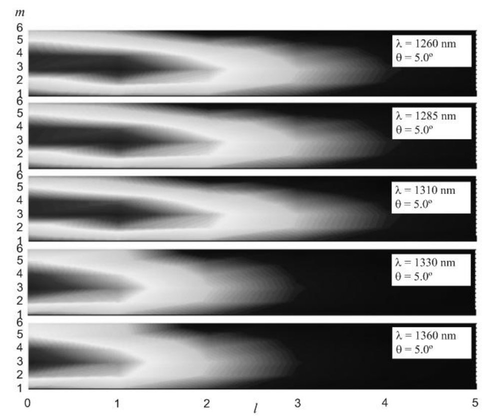


Figure 13. Diagram of normalized mode amplitudes of the excited modes of the researched MMF at the input of the fundamental mode LP_{01} and the high order mode LP_{11} of equal power from SM LD output via SMF at the fixed angular offset θ=5° and the set optical carrier λ.

4. CONCLUSIONS

The mathematical description of excitement of weakly guiding graded multimode optical fibers with arbitrary axially symmetric refractive index profile allowing to consider features of signal input in fiber end, in particular, mode structure for a signal of a light source, and also existence/lack of an axial or angular offset is submitted. The proposed approach is based on calculation of mode coupling coefficients for launched modes with excited modes in optical fiber which is implemented by combined use of earlier developed EMGA method and overlap field integral method. The calculation method for mode coupling coefficients of described splice of optical fibers. The analysis of power rescheduling of the optical signal, excited by a coherent light source in "O" - band, which terminated by standard SMF ITU-T G.652, between the guided modes of silica graded MMF with large technological defect of a refractive index profile in the core center in the dip form is carried out.

It is revealed that not only zero order modes LP_{0m}, but also the first azimuthal order modes LP_{1m} are excited in MMF at signal launching from SM LD output on λ=1310 nm via SMF in the conditions of the aligned input or input with radial offset. On the one hand, it is coming from the fact that some industrial samples of SMF doesn't lock propagation of a mode LP_{11} because last meets a cut-off condition up to optical carrier λ=1325 nm inclusively, and the generated by standard LD optical signal on the same operation wavelength in addition to fundamental mode LP_{01} may contain parasitic transverse high order modes. On the other hand, the analysis of possible connection schemes for MMF to standard terminated SM LD showed existence of a splice "LD – matching SMF" which characterized by some angular offset. In this case mode LP_{11} will be also launched in SMF in addition to the fundamental mode, so further the modes LP_{1m} will appear in MMF even at coaxial connection of the specified matching lightguide and MMF of fiber optic line. In turn, on a splice "SMF – MMF" adding of higher azimuthal order modes is possible at the angular offset.

Diagrams of the normalized amplitudes of the excited modes in the researched MMF for the set input conditions for a signal from LD output are plotted. Calculation of spectral characteristics of mode coupling coefficients on a splice "matching SMF – graded MMF with the central dip of a refractive index profile" is carried out. The calculation results allowed to localize values of axial and angular offset at which excitation is reached as it is possible large number of the guided modes with the smallest variation of amplitudes what leads to strengthening of DMD effect. At the same time, if DMD is a key negative factor of optical signal distortion from the viewpoint of bandwidth limitation of fiber optic transmission lines functioning in the few-mode regime, then such strong DMD effect, on the contrary, is required for MMF sensor networks on few-mode effects. Spectral characteristics of mode coupling coefficients on the described splice in "O" - band for the set values of precision radial or angular offset are plotted. It is shown that in the central area of "O" - band, corresponding to neighborhoods of the optical carrier λ=1310±10 nm, the power distribution between the guided modes of the excited MMF, in general, remain.

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REFERENCES

[1] Listvin, A.V., Listvin, V.N., Shvyrkov, D.V., [Optical fibers for communication lines], LESARart, Moscow, 288 (2003).
[2] Smirnov, I.G., [Premises cable systems: design, installation and certification], Econ-Inoform, Moscow, 360 (2005).
[3] Semenov, A.B., [Fiber optical subsystems of modern premises cable systems], Akademiya IT, DMK Press, Moscow, 632 (2007).
[4] Roberts, C. and Ellis, R., "Fiber selection and standards guide for premises networks," Corning White Paper, 8 (2013).
[5] Irujo, T., "OM4 fiber – the next generation of multimode fiber," FOLS Webconference materials, http://www.fols.org/fols_library/ archived_webvonferences/index.cfm (2010).
[6] Bottacchi, S., [Multi-Gigabit transmission over multimode optical fibre. Theory and design methods for 10GbE systems], John Wiley & Sons Ltd., West Sussex, 654 (2006).
[7] Bourdine, A.V., [Few-mode regime of optical signal transmission via multimode fibers: applications in modern infocommunication], PSUTI, Samara,274 (2001).
[8] Bourdine, A.V., Fedorov, A.A., Kafarova, A.M., Minaeva A.Yu. and Seregina Yu.A., "Results of experimental approbation of the interferometric scheme for registration of external mechanical influences on the multimode optical fiber functioning in the few-mode regime," XIII International scientific and technical conference "Physics and Technical Applications of Wave Processes", 195-197 (2015).
[9] Kafarova, A.M., Faskhutdinov, L.M., Kuznetzov, A.A., Minaeva, A.Yu., Sevruk, N.L., Nureev, I.I., Vasilets, A.A., Bourdine, A.V., Morozov, O.G. and Burdin, V.A., "Quasi-interferometric scheme improved by fiber Bragg grating for detection of outer mechanical stress influence on distributed sensor being silica multimode optical fiber operating in a few-mode regime," Proc. of SPIE 9807, 98070K (2016).
[10] Bourdine, A.V., Dmitriev, E.V., Praporshchikov, D.E. and Sevruk, N.L., "Application of silica multimode optical fibers with large central defect of refractive index profile for fiber optic sensors based on a few-mode effects," Prikladnaya fotonika 3(3), 252-279 (2016).
[11] Sheremeteva, A.Yu., Kafarova, A.M., Sevruk, N.L., Evtushenko, A.S. and Tsarev, A.A., "Research of influence of the central defect of a refractive index profile of multimode optical fibers at external mechanical impact on a pulse response of the few-mode signal registered at the output of the quasi-interferometric scheme," International scientific and technical conference of young scientists, graduate students and students "Applied electrodynamics, photonics and live systems", 224-226 (2016).
[12] Bourdine, A.V., Vasilets, A.A., Burdin, V.A. and Morozov, O.G., "Distributed sensor on the multimode optical fibers, added with a fiber Bragg grating, functioning in the few-mode signal transmission regime," Foton Ekspress 6(134), 12-13 (2016).
[13] Bourdine, A.V., Burdin, V.A., Vasilets, A.A., Morozov, O.G., Kafarova, A.M., Kuznetzov, A.A., Nureev, I.I., Sevruk, N.L., Faskhutdinov, L.M. and Sheremeteva, A.Yu., " Research of spectral responses of the silica multimode fiber lightguides with large central defect of a graded refractive index profile added with a fiber Bragg grating," XIV The international scientific conference "Optical technologies in telecommunications" (OTT-2016), 241-243 (2016).
[14] Okosi, T., [Fiber optical sensors], Energoatomizdat, Leningrad, 256 (1990).
[15] Grattan, L.S. and Meggitt, B.T. [Optical Fiber Sensor Technology. Fundamentals], Springer Science, New York, 325 (2000).
[16] Kulchin, Yu.N., [Distributed fiber optical measuring systems], Fizmatlit, Moscow, 272 (2001).
[17] Rajan, G., [Optical Fiber Sensors: Advanced Techniques and Applications (Devices, Circuits, and Systems)], CRC Press/Taylor & Francis, Boca Raton, FL, USA, 575 (2015).
[18] Liu, Yu. and Wei, Li, "Low-cost high-sensitivity strain and temperature sensing using graded-index multimode fibers," Applied Optics 46(13), 2516-2519 (2007).
mismatched parameters," IEEE Journal of Lightwave Technology 10(11), 1521-1526 (1992).

[19] Pinet, E., Cibula, E. and Donlagic, D., "Ultra-miniature all-glass Fabry-Pérot pressure sensor manufactured at the tip of a multimode optical fiber," Proc. of SPIE 6770, 67700U (2007).
[20] Liu, L., Gong, Yu., Wu, Yu., Zhao, T., Wu, H.-J. and Rao, Y.-J., "Spatial frequency multiplexing of fiber-optic interferometric refractive index sensors based on graded-index multimode fibers," Sensors 12, 12377-12385 (2012).
[21] Luo, Yi., Xia, Li, Yu, C., Li, W., Sun, Q., Wang, Yu. and Liu, D., "Multi-parameter optical fiber sensor based on enhanced multimode interference," Optics Communications 344(1), 120-124 (2015).
[22] Xue, H., Meng, H., Wang, W., Xiong, R., Yao, Q. and Huang, B., "Single-mode-multimode fiber structure based sensor for simultaneous measurement of refractive index and temperature," IEEE Sensors Journal 13(11), 4220-4223 (2013).
[23] Li, A., Wang, Yi., Hu, Q. and Shieh, W., "Few-mode fiber based optical sensors," Optics Express 23(2), 1139-1150 (2015).
[24] Del Villar, I., Socorro, A.B., Hernaez, M., Corres, J.M., Zamarreño, C.R., Sanchez, P., Arregui, F.J. and Matias, I.R., "Removed multimode optical fiber and single-mode multimode single-mode fiber: a comparative study," Journal of Sensors 2015, 763762 (2015).
[25] Li, D., Gong, Yu. and Wu, Yu., "Tilted fiber Bragg grating in graded-index multimode fiber and its sensing characteristics," Photonic Sensors 3(2), 112-117 (2013).
[26] Song, D., Fang, S., Li, B., Zh., J. and Sun, W., "Multi-parameter sensing based on graded-index multimode fiber," Proc. of Imaging and Applied Optics, JTu4A.29 (2013).
[27] Fang, Sh., Li, B., Song, D., Zhang, J., Sun, W. and Yuan, L., "A smart graded-index multimode fiber based sensor unit for multi-parameter sensing applications," Optics and Photonics Journal 3, 265-267 (2013).
[28] Guo, T., Guan, B.-O. and Albert, J., "Polarimetric multi-mode tilted fiber grating sensors," Optics Express 22(6), 7330-7336 (2014).
[29] Schmid, M.J. and Muller, M.S., "Measuring Bragg gratings in multimode optical fibers," Optics Express 23(6), 8087-8094 (2015).
[30] Kulikov, A. and Ignat`ev, A., " Review of fiber optical perimeter protection systems," Algoritmy bezopasnosti 4, 56-61 (2010).
[31] Liokumovich, L.B., Ushakov, N.A., Kotov, O.I., Bisyarin, M.A. and Hartog, A.H., "Fundamentals of optical fiber sensing schemes based on coherent optical time domain reflectometry: signal model under static fiber conditions," IEEE Journal of Lightwave Technology 33(17), 3660-3671 (2015).
[32] Gorbachev, O., " Interferential researches of speckle-structures in an optical cable," Fotonika 6 (36), 20-24 (2012).
[33] Lujo, I., Klokoc, P., Komljenovic, T., Bosiljevac, M. and Sipus, Z., "Fiber-optic vibration sensor based on multimode fiber," Radioengineering 17(2), 93-97 (2008).
[34] Rodriguez-Cobo, L., Lomer, M., Galindez, C. and Lopez-Higuera, J.M., "Speckle characterization in multimode fibers for sensing applications," Proc. of SPIE 8413, 84131R (2012).
[35] Bourdine, A.V., "Differential mode delay of different generation silica multimode fibers," Foton-Express 5-6(69-70), 20-22 (2008).
[36] Bourdine, A.V. and Yablochkin, K.A., "Investigation of refractive index profile defects of silica graded-index multimode fibers of telecommunication cables," Infokommunikacionnye Tehnologii 2, 22-27 (2010).
[37] Bourdine, A.V., Dmitriev, E.V., Praporshchikov, D.E. and Sevruk, N.L., "Application of silica multimode optical fibers with large central defect of refractive index profile for fiber optic sensors based on a few-mode effects," Prikladnaya fotonika 3(3), 252-279 (2016).
[38] Raddatz, L., White, I.H., Cunningham, D.G. and Nowell, M.C., "An experimental and theoretical study of the offset launch technique for the enhancement of the bandwidth of multimode fiber links," IEEE Journal of Lightwave Technology 16(3), 324-331 (1998).
[39] Webster, M., Raddatz, I., White, I.H. and Cunningham, D.G., "A statistical analysis of conditioned launch for Gigabit Ethernet links using multimode fiber," IEEE Journal of Lightwave Technology 17(9), 1532-1541 (1999).
[40] Srapionov, V.A., "Mode coupling in splices of optical fibers with parameters variation," Elektrosvyaz` 10, 10-12 (1985).
[41] Gurdzhi, S.P. and Katok, V.B., " Calculation of losses in splices of singlemode lightguides with a difficult refractive index profile," Elektrosvyaz` 10, 25-27 (1990).
[42] Meunier, J.P. and Hosain, S.I., "An accurate splice loss analysis for single-mode graded-index fibers with

[43] Yu, Q., Zongo, P.-H. and Facq, P., "Refractive index profile influences on mode coupling effects at optical fiber splices and connectors," IEEE Journal of Lightwave Technology 11(8), 1270-1273 (1993).
[44] Chandra, R., Thyagarajan, K. and Ghatak, A.K., "Mode excitation by tilted and offset Gaussian beams in W-type fibers," Applied Optics 17(17), 2842-2847 (1978).
[45] Avruckiy, I.A, Sychugov, V.A. and Tischenko, A.V., " Research of processes of excitement, radiation and reflection of light in corrugated wave guides," Trudy IOFAN 34, 3-98 (1991).
[46] Hosain, S.I., Meunier, J.P. and Wang, Z.H., "Coupling efficiency of butt-joined planar waveguides with simultaneous tilt and transverse offset," IEEE Journal of Lightwave Technology 14(5), 901-907 (1996).
[47] Snyder, A.W. and Love, J., [Optical waveguide theory], Chapman & Hall, 738.
[48] Gholami, A., Molin, D. and Sillard, P., "Physical modeling of 10 GbE optical communication systems," IEEE Journal of Lightwave Technology 29(1), 115-123 (2011).
[49] Pepeljugoski, P., Golowich, S.E., Ritger, A.J., Kolesar, P. and Ristetski, A., "Modeling and simulation of next-generation multimode fiber links," IEEE Journal of Lightwave Technology 21(5), 1242-1255 (2003).
[50] Meher, H. and Hosain, S.I., "Variational approximations for single-mode graded-index fibers: some interesting applications," Journal of Optical Communications 24(1), 25-30 (2003).
[51] Sharma, A., Hosain, S.I. and Ghatak, A.K., "The fundamental mode of graded-index fibres: simple and accurate variational methods," Optical and Quantum Electronics 14(1), 7-15 (1982).
[52] Tewari, R., Hosain, S.I. and Thyagarajan, K., "Scalar variational analysis of single mode fibers with Gaussian and smoothed-out profiles," Optics Communications 48(3), 176-180 (1983).
[53] Oksanen, M.I. and Lindell, I.V., "Variational analysis of anisotropic graded-index optical fibers," IEEE Journal of Lightwave Technology 7(1), 87-91 (1989).
[54] Ankiewicz, A. and Peng, G.-D., "Generalized Gaussian approximation for single-mode fibers," IEEE Journal of Lightwave Technology 10(1), 22-27 (1992).
[55] Holmes, M.J., Spirit, D.M. and Payne, F.P., "New Gaussian-based approximation for modeling non-linear effects in optical fibers," IEEE Journal of Lightwave Technology 12(2), 193-201 (1994).
[56] Wu, M.-Sh., Lee, M.-H. and Tsai, W.-H., "Variational analysis of single-mode graded-core W-fibers," IEEE Journal of Lightwave Technology 14(1), 121-125 (1996).
[57] Adams, M.J., [An introduction to optical waveguides], John Wiley and Sons, New York, 401 (1981).
[58] Bourdine, A.V., Praporshchikov, D.E. and Yablochkin, K.A., "Investigation of defects of refractive index profile of silica graded-index multimode fibers," Proc. of SPIE 7992, 799206 (2011).
[59] Bourdine, A.V., "Modeling and simulation of piecewise regular multimode fiber links operating in a few-mode regime," Advances in Optical Technologies 2013, 469389 (2013).
[60] Bourdine, A.V. and Zhukov, A.E., "Fast approximate method for VCSEL-MMF transverse mode coupling analysis," Telecommunications and Radio Engineering 7(11), 979-999 (2016).
[61] Bourdine, A.V. and Delmukhametov, O.R., "Calculation of transmission parameters of the launched higher-order modes based on the combination of a modified Gaussian approximation and a finite element method," Telecommunications and Radio Engineering 72(2), 111-123 (2013).
[62] ITU COM 15-273-E, "Definition and test methods for the relevant parameters of single-mode fibres," (1996).
[63] Bourdine, A.V., Delmukhametov, O.R., Zhukov, A.E. and Chekalov, A.S., "Fast and simple method for calculation of the mode field diameter of arbitrary order guided mode in weakly-guiding optical fibers," Proc. of SPIE 9533, 95330F (2015).
[64] Gradshtein, I.S. and Ryzhik, I.M., [Tables of integrals, series and products], Fizmatgiz, Moscow, 1100 (1962).
[65] Abramovetz, M. and Stegun, I., [Handbook of mathematical functions], Nauka, Moscow, 830 (1979).