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Optimization of step index fiber for bright soliton propagation

Abstract. *The paper presents optimization results of step index fiber, which cladding is made of pure silica glass. The aim of optimization is to maximize simultaneously the range of single-mode operation and anomalous dispersion regime in the vicinity of the third telecommunications window while minimizing the peak power of the fundamental soliton.*

Streszczenie. *W artykule zostaną zaprezentowane wyniki optymalizacji światłowodu skokowego, którego płaszcz jest wykonany z czystego szkła kwarcowego. Celem optymalizacji jest jednoczesna maksymalizacja zakresu pracy jednomodowej oraz dyspersji anomalnej w pobliżu trzeciego okna transmisyjnego zapewniając minimalizację mocy szczytowej solitonu podstawowego. (**Optymalizacja światłowodu skokowego dla propagacji solitonu jasnego**).*

Keywords: step-index optical fiber, soliton, dispersion characteristic, eigenvalue equation.
Słowa kluczowe: światłowód skokowy, soliton, charakterystyka dyspersyjna, równanie wartości własnych.

Introduction

Optical fibers are widely used in measurements of physical quantities [1], in electro-optical bistable switches [2], in passive optical networks [3] and in spectrophotometric measurements of flame emission spectra [4]. First publication concerning optimization of step-index fiber, which core was made of pure silica glass appeared in 2008 [5]. The aim of optimization was to maximize simultaneously the single mode operating and anomalous dispersion range. In 2009, a publication was issued devoted to optimization of the fiber, which core was made of silica glass with fluorine doped [6]. In the mentioned above publications, both core and cladding were determined by the value of the refractive indices resulting from the Sellmaier dispersion formula [5]. The Sellmeier formula coefficients depend on the type and amount of silica glass dopant decreasing (fluorine) or increasing (germanium dioxide) the value of the refractive index. In view of the fact that a particular chemical composition of core and cladding is approximately equal to one and constant, as a function of changes in the wavelength range from 1 to 2 *μm*, value of the absolute difference of refractive indices of core and cladding ($\Delta n=n_1-n_2\approx$const), it is impossible to determine the optimum value of normalized frequency V_{OPT} as a function of the absolute difference of refractive indices Δn, i.e. $V_{OPT}=f(\Delta n)$ in a satisfactory manner. In this article, in order to increase the generality of considerations and a more precise examination of changes of the dispersion characteristic in the optimization process, it was decided to dispense with defining the chemical composition of the two layers of step index fiber, limiting the definition only to the last layer, i.e. to the cladding. Therefore, it was assumed that the refractive index of the cladding n_2 was determined from the Sellmeier dispersion formula [1] for pure silica glass. The value of the refractive index of the core n_1 was determined based on the following relationship $n_1=\Delta n+n_2$, where Δn was the input quantity in the optimization process.

Method

The single-mode step index optical fibers are produced in several variants. As a rule, in all variants the diameter of the protective coating $2c\approx250$ *μm*, while the diameter of the cladding $2\cdot b\approx125$ *μm* (Fig. 1). In the basic embodiment, the core diameter $2a\approx9$ *μm*, the effective radius of the fundamental mode ω_{EFF} is about 10% higher.

If the cladding is made of pure silica glass (100 m% SiO_2) while the core of silica glass doped with germanium dioxide GeO_2 at 3.1 m% (3.1 m% GeO_2, and 96.9 m% SiO_2), then for wavelength $\lambda\approx1.550$ *μm* core refractive index $n_1\approx1.449$, while the refractive index of cladding $n_2\approx1.444$. Consequently, the absolute difference in refractive indices $\Delta n=n_1-n_2\approx0.005$, while the normalized frequency $V\approx2.2$. These parameters corresponds to a definite value of the cutoff wavelength of the second mode $\lambda_C\approx1.42$ *μm* (above which extends the single mode operation) and the wavelength of zero chromatic dispersion and group velocity dispersion $\lambda_{ZD}\approx1.30$ *μm* (above which pulses fall within the anomalous dispersion range). Generation of bright solitons in such an optical fiber is possible only when the working wavelength $\lambda_{OPER}>\lambda_C\approx1.42$ *μm* because only in this case single mode operating range will coincides with the anomalous dispersion range. The sufficient condition for generation of fundamental soliton is pulse peak power P_0, which is dependent on the value of group velocity dispersion β_2, the fiber nonlinearity coefficient γ (which is a function of the transverse electric field component of the fundamental mode and the fiber nonlinearity coefficient) and the initial pulse width T_0. For the operating wavelength $\lambda_{OPER}\approx1.55$ *μm*, $\beta_2\approx-23$ ps^2/km, $\gamma\approx1$ $(W\cdot km)^{-1}$, and assuming that the initial pulse width $T_0\approx1$ ps, peak power of the fundamental soliton $P_0\approx23$ *W*.

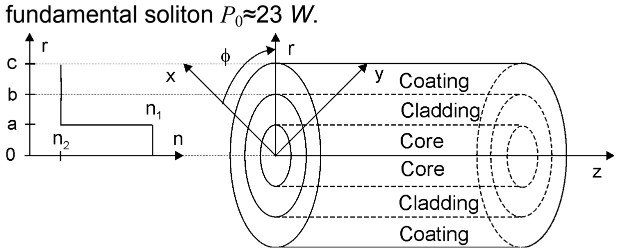

Fig.1. Single-mode step-index optical fiber with a refractive index profile in a cylindrical coordinate system

Optimization of such a step index fiber can be carried out in two ways. First, by decreasing the value of the normalized frequency *V* and thereby reducing the value of the fiber core radius (a) it is possible to reduce the cut-off wavelength λ_C and simultaneously to increase the wavelength of zero chromatic dispersion (group velocity dispersion) λ_{ZD} and obtain approximate equality $\lambda_{ZD}\approx\lambda_C$. It guarantees both maximizing of single-mode operation and anomalous dispersion regime. It should be noted that the simultaneous fulfillment of the single-mode condition and anomalous dispersion range is a prerequisite for generation of bright soliton inside optical fiber. Simultaneous maximization of both scopes increases the range of wavelengths that can be used in the process of wavelength division multiplexing (WDM, CWDM, DWDM and UDWDM). The first type of optimization is closely related to the chemical composition of core and cladding. It means that if the cladding is made of pure silica glass (100 m% SiO_2) and the core is made of silica glass doped with germanium dioxide at 3.1 m% (3.1 m% GeO_2, and 96.9 m% SiO_2) there exists only one optimal value of normalized frequency V_{OPT} (which corresponds to only one optimal value of core radius a_{OPT}). It guarantees fulfillment of condition $\lambda_{ZD}\approx\lambda_C$.

The second type of optimization is associated with increasing quantities of GeO_2 dopant in the core, i.e. a change in chemical composition of the core. It turns out that increasing the amount of GeO_2 shifts the optimized dispersion characteristics in longer waves direction (resulting in decreasing the value of dispersion parameter *D* and $|\beta_2|$ in the vicinity of the third transmission window) and reduction the value of effective mode area of the fundamental mode A_{EFF}. The size of which has a direct impact on fiber nonlinearity parameter *γ*, since A_{EFF}~1/γ. Reducing the value of parameter *D,* while increasing the value of *γ,* reduces the peak power of the fundamental soliton P_0. However, even after increasing GeO_2 doping in the core to a level of 13.5 m%, which results in increased value of $n_1 \approx 1.466$ and thus increasing the value of $\Delta n=n_1-n_2\approx 0.022$ cannot change monotonicity of dispersion characteristics in the wavelength range from 1 to 2 *μm*. Increasing the absolute refractive indices difference Δn above $\Delta n\approx 0.022$ allows changing the nature of dispersion characteristics within the range of 1 to 2 *μm* in such a way, that the characteristics has two zeros and a local maximum. Assuming that cladding of step-index fiber is made of pure silica glass, optimal value of Δn parameter was found, guaranteeing reduction in values of *D* below 0.2 *ps*/(*km nm*) ranging from 1.480 to 1.634 *μm*.

Optimization of step-index fiber is discussed in detail in [5, 6]. The key equation used in the optimization process was eigenvalue equation of step-index fiber of the form [5, 6]:

$$\left(Y_m + X_m\right)\left(Y_m n_1^2 + n_2^2 X_m\right) - \left(\frac{\beta m}{k}\right)^2 \left(\frac{1}{u^2} + \frac{1}{w^2}\right)^2 = 0 \quad (1)$$

where $Y_m=J_m'(u)/(uJ_m(u))$, $X_m=K_m'(w)/(wK_m(w))$, β is a phase constant, k – wave number, $u=a\chi=a(k^2n_1^2-\beta^2)^{1/2}$, $w=a\gamma=a(\beta^2-k^2n_2^2)^{1/2}$, $J_m(\chi r)$ is the Bessel function of first kind of *m-th* order, while the $K_m(\gamma r)$ is the modified Bessel function of second kind of *m-th* order. The prim means differentiating with respect to the argument of Bessel functions. For the fundamental mode, modal azimuthal number *m* is equal to 1. Moreover, it is worth noting that the designation of zero chromatic dispersion *D* and the group velocity dispersion of β_2 was carried out using the rational interpolation algorithm [7].

Results

The results of calculations are in the form of graphs and tables. Figure 2 shows a set of dispersion characteristics of the HE_{11} mode (in the range *μm*<*λ*<2 *μm*) obtained as a result of optimizing the step-index-type fiber, assuming that cladding is made of pure silica glass and refractive index of core is calculated from the following relationship $n_1=n_2+\Delta n$.

Figure 3 shows a set of dispersion characteristics of HE_{11} mode (in the vicinity of the third transmission window) obtained as a result of optimizing step-index fiber when value of parameter Δn was changing.

Figure 4 shows a set of dispersion characteristics of HE_{11} mode (in the vicinity of the third transmission window) obtained as a result of optimizing step-index fiber when value of parameter Δn was constant and equal $\Delta n=0.041$ and value of the difference $\lambda_{ZD1}-\lambda_C$ was changing.

Table 1 contains selected results of optimizing step-index fiber ankle; where V_{OPT} is optimized value of normalized frequency; a_{OPT} is optimized value of core radius; ω_{EFF} – effective core radius of HE_{11} mode (calculated according to the relation given in [5, 6, 8, 9]); A_{EFF} – effective core area of HE_{11} mode (determined by the formula provided in [5, 6, 8, 9]); γ – nonlinear parameter of fiber (calculated according to the relation given in [5, 6, 8, 9]); λ_C – wavelength at which TE_{01} mode is cut-off; λ_{ZD1} – first zero on the chromatic dispersion *D* and group velocity dispersion characteristic β_2; λ_{MAX} – local maximum on the chromatic dispersion characteristic *D*, and local minimum on the group velocity dispersion characteristics β_2; λ_{ZD2} – second zero on the chromatic dispersion *D* and group velocity dispersion characteristic β_2; *D* – chromatic dispersion (assuming that the wavelength λ=1.55*μm*); β_2 – group velocity dispersion (by assumption that the wavelength λ=1.55*μm*); P_0 – peak power of fundamental soliton (calculated according to the relation given in [5, 6, 8-11] assuming that initial pulse width is equal T_0=1*ps*); A_0 – peak amplitude value of the fundamental soliton (determined by the formula provided in [5, 6, 8-11] by assumption that initial pulse width is equal T_0=1*ps*); L_D – dispersion length (calculated according to the relation given in [5, 6, 8-11] assuming that initial pulse width is equal T_0=1*ps*); z_0 – soliton period (determined by the formula provided in [5, 6, 8-11] by assumption that initial pulse width is equal T_0=1*ps*).

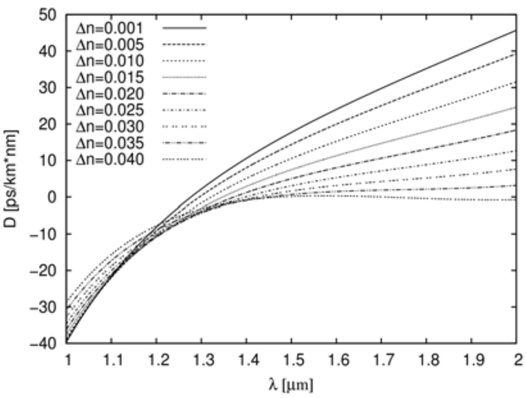

Fig.2. Set of dispersion characteristics of HE_{11} mode for 1 *μm*<*λ*<2 *μm* obtained as a result of optimizing step-index fiber when value of parameter Δn was changed

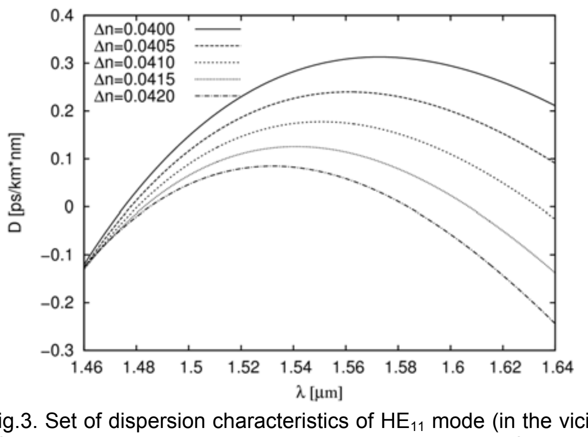

Fig.3. Set of dispersion characteristics of HE_{11} mode (in the vicinity of the third transmission window) obtained as a result of optimizing step-index fiber when value of parameter Δn was changed

Discussion

It can be concluded that increasing the amount of dopant, which increases the value of the refractive index of the core relative to the cladding, accompanied by not only the shift of zero of dispersion characteristics, but also a change of character of the chromatic dispersion curve from standard (monotonically increasing) to flattened in the vicinity of third transmission window as shown in Figure 2 and 3. Increase the value of parameter Δn over Δn=0.035 on the dispersion characteristics, there occurs a local maximum and second zero in the range from 1 to 2 *μm*. It is noteworthy that for each of the characteristics, the condition of $\lambda_{ZD1} \approx \lambda_C$ was met. Figure 3 shows selected dispersion characteristics of step-index fiber in the vicinity of the third transmission window for value of parameter Δn varying from Δn=0.040 to Δn=0.042 to. It turns out that if value of parameter Δn increases, local maximum shifts towards shorter wavelengths, maximum value of dispersion parameter decreases and anomalous dispersion range also decreases. The zeros and the local maxima of the dispersion characteristics shown in Figure 3 along with parameters of fiber and fundamental soliton generated are shown in column 3, 4, 5, 8 and 9 of Table 1. Based on selected results of step-index fiber optimization shown in Figure 3 and in columns 3, 4, 5, 8 and 9 of Table 1 it can be concluded that the optimal value of parameter Δn_{OPT} is equal to 0.041. If $\Delta n = \Delta n_{OPT}$=0.041 then local maximum of dispersion characteristic coincides exactly with local minimum of attenuation characteristic of silica glass fiber, i.e. for wavelength λ equal λ=1.55 *μm*. Figure 4 shows the effect of non-compliance with condition $\lambda_{ZD} \approx \lambda_C$ on optimized, from the viewpoint of parameter value Δn (i.e. for $\Delta n = \Delta n_{OPT}$=0.041), dispersion characteristics of step-index fiber. It turns out that the increase in value of the difference $\lambda_{ZD} - \lambda_C$ decreases the value of local maximum on dispersion characteristic, which is accompanied by anomalous dispersion range reduction. Selected results of the optimization associated with Figure 4 are shown in columns 5, 6 and 7 of Table 1.

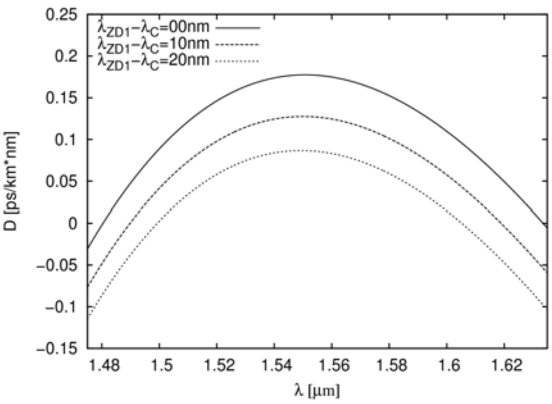

Fig.4. Set of dispersion characteristics of HE_{11} mode (in the vicinity of the third transmission window) obtained as a result of optimizing step-index fiber when value of parameter Δn was constant and equal Δn=0.041 and value of the difference $\lambda_{ZD1} - \lambda_C$ was changed

Conclusions

On the basis of the presented optimization of step-index fiber it can be concluded that by the appropriate selection of the chemical composition of the core and its radius the dispersion characteristics will have a local maximum in the vicinity of the third transmission window. The optimized value of parameter Δn is $\Delta n = \Delta n_{OPT}$=0.041. If $\Delta n = \Delta n_{OPT}$=0.041 and $a = a_{OPT}$=1.635 *μm*, then maximum value of parameter D within the range of 1 to 2 *μm*, is equal to D=0.177 $ps \cdot km^{-1} \cdot nm^{-1}$. The accompanying peak power of the fundamental soliton P_0 is equal to 26.84 *mW*. Such a low value of P_0 guarantees the possibility of the fundamental soliton generation using commercially available semiconductor lasers that are currently used in fiber-optic communication systems. The range of bright solitons generation is in the optimal case (Δn_{OPT}=0.041 and a_{OPT}=1.635 *μm*) limited only by scope of anomalous dispersion, which begins from λ_{ZD1}=1.480 *μm* and finishes at λ_{ZD2}=1.634 *μm*. It is worth noting that there is a possibility of further reducing the value of the parameter P_0 below P_0=26.84 *mW*, but it involves limitation of anomalous dispersion range.

Table 1. Selected results of step-index fiber optimization

Parameter	Unit	Δn= 0.0400	Δn= 0.0405	Δn_{OPT}= 0.0410	Δn_{OPT}= 0.0410	Δn_{OPT}= 0.0410	Δn= 0.0415	Δn= 0.0420
V_{OPT}	-	2.288	2.292	2.296	2.295	2.295	2.300	2.304
a_{OPT}	*μm*	1.649	1.642	1.635	1.634	1.633	1.627	1.620
ω_{EFF}	*μm*	1.855	1.845	1.843	1.834	1.834	1.825	1.815
A_{EFF}	μm^2	10.81	10.69	10.57	10.57	10.57	10.46	10.35
γ	$km^{-1}\ W^{-1}$	8.249	8.342	8.435	8.438	8.440	8.528	8.620
λ_C	*μm*	1.475	1.479	1.480	1.480	1.479	1.483	1.485
λ_{ZD1}	*μm*	1.475	1.479	1.480	1.490	1.499	1.483	1.485
λ_{MAX}	*μm*	1.573	1.560	1.550	1.550	1.550	1.541	1.532
λ_{ZD2}	*μm*	1.700	1.664	1.634	1.619	1.605	1.607	1.584
D	$ps \cdot km^{-1} \cdot nm^{-1}$	0.299	0.236	0.177	0.128	0.087	0.123	0.074
β_2	$ps^2 \cdot km^{-1}$	-0.381	-0.301	-0.226	-0.162	-0.110	-0.157	-0.094
P_0	*mW*	46.17	36.12	26.84	19.29	13.09	18.38	10.88
A_0	-	0.215	0.190	0.164	0.139	0.114	0.136	0.104
L_D	*km*	2.625	3.319	4.417	6.145	9.052	6.380	10.66
z_0	*km*	4.124	5.214	6.938	9.653	14.22	10.02	16.74

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