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EQUILIBRIUM MODE DISTRIBUTION IN W-TYPE GLASS OPTICAL FIBERS

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Abstract: Power flow equation is used to calculate equilibrium mode distribution in W-type glass optical fibers. It has been shown how the coupling length for achieving the equilibrium mode distribution in W-type glass optical fibers varies with the depth and width of the intermediate layer and coupling strength for different widths of launch beam distribution. W-type optical fibers have shown effectiveness in reducing modal dispersion and bending loss.

Keywords: W-type glass optical fibers; mode coupling.

1. INTRODUCTION

Glass optical fibers with single cladding (SC) are the transmission medium for most long-distance communication or high-capacity networks Application of plastic optical fibers (POFs) in communication has been limited to short data links and local area networks because of comparatively high attenuation and modest bandwidth of these fibers that limited the transmission rate. Attempts to overcome these performance confines included spatial modulation [1] and detection techniques [2], equalization [3], modal dispersion compensation [4], and restricted modal launch. Yet, comparatively little attention was devoted to the analysis and design of multimode fiber design with a view of advancing fiber characteristics, particularly its transmission bandwidth. With their intermediate layer, three-layered W-type POFs have a potential in this respect as their bandwidths were shown experimentally to exceed those of graded index POFs [5].

Waveguide dispersion is smaller in the W-type fiber than it is in the SC fiber. It has a wide transmission bandwidth and lower bending losses compared to a corresponding SC fiber because the number of guided modes in the W-type fiber is reduced. The reduction is by the intermediate layer, which decreases the fiber's effective numerical aperture and therefore the number of guided modes, and confines the guided modes tighter to the core [6]. In the case of glass optical fibers, while the bandwidth-distance product is typically around 30 MHz·km for the SC variety, it is around 50 MHz·km for the W-type. For POFs, these figures would typically be 15 MHz·km for the SC and 200 MHz·km for the W-type [5,7–9] fibers.

Differential mode-attenuation and mode coupling strongly affect the transmission performance of multimode optical fibers. The former is a consequence of absorption and scattering of light within the fiber material, which reduces the transmitted power. The latter is a form of light diffraction, which transfers power between individual modes and is caused by random fiber-anomalies (such as cracks, voids, microscopic bends, and density and diameter/shape variation). On the positive side, mode coupling reduces modal dispersion thus increasing fiber bandwidth. Namely, the transfer of energy between modes with different propagation velocities tends to average out the total propagation delays, thus reducing the intermodal dispersion and increasing the fiber bandwidth. The negative consequence of mode coupling is that it increases fiber loss, especially in curved fiber [10], changes properties of the output-field and degrades the quality of the beam. With their intermediate layer situated in-between the cladding and core, W-type fiber properties differ from the ones pertaining to SC fibers. This is because of the lossy leaky modes that are found in the intermediate layer. The coupling of modes from guided to lossy leaky ones in W-type fibers was not sufficiently explained in the literature. Bends and junctions of the fiber are expected in any optical fiber network including W-type fiber network, representing one more cause of coupling. It causes the energy carried by the low-

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order modes to couple to higher order ones. Consequently, regardless of whether only the low-order modes were launched by selectively restricted conditions, higher order modes will always appear in the output. Such higher order modes reduce the bandwidth of the W-type fiber and necessitate that the group delay difference between modes be minimized by optimizing the fiber's refractive index profile [11]. As modal attenuation, coupling and dispersion affect the transmission of the W-type optical fiber, methods for calculating their contributions are needed.

The far-field pattern of an optical fiber is determined by the optical power distribution that depends on the launch conditions, fiber properties and fiber length. Light launched at a specific angle $\theta_0 > 0$ with respect to the fiber axis will form a sharply defined ring radiation pattern at the output end of only short fibers. Because of mode coupling, the boundary (edges) of such a ring becomes fuzzy at the end of longer fibers. Up to a "coupling length" L_c from the input fiber end, the extent of this fuzziness increases further with fiber length and the ring-pattern evolves gradually into a disk extending across the entire fiber cross-section. An equilibrium mode distribution (EMD) exists beyond the coupling length L_c of the fiber. It is characterized by the absence of rings regardless of launch conditions, even though the resulting light distribution of the disk-pattern may vary with launch conditions. EMD indicates a substantially complete mode coupling. It is of critical importance when measuring characteristics of multimode optical fibers (linear attenuation, bandwidth, etc). Indeed, measurement of these characteristics would only be considered as meaningful if performed at the EMD condition when it is possible to assign a unique value of loss per unit length to a fiber [12].

In order to determine the fiber length L_c where the EMD is achieved, one can perform either pulse broadening measurements as a function of fiber length [13, 14] or can analyze the change of the output angular power distribution as a function of fiber length for different launch angles [14]. In the former case, L_c is the fiber length after which the bandwidth becomes proportional to $1/z^{1/2}$ instead of $1/z$ (z is the fiber length). In the latter case, L_c is the fiber length after which all output angular power distributions take the disk-form regardless of the incidence angle. The shorter the length L_c, the earlier the bandwidth switches from the functional dependence of $1/z$ to $1/z^{1/2}$ (faster bandwidth improvement).

Much work has been reported about the angular power distribution across the near and far field output from the fiber end. The use of the power flow equation was reported in determining these distributions and predicting them for the given fiber length and launch input; whereby the power transfer between modes as the rate of mode coupling was modeled by the coupling coefficient D [13, 15–20]. Adding to this approach, in this paper we investigated how the width of the launch beam distribution influences the coupling length for achieving the equilibrium mode distribution in W-type glass optical fibers for various depths and widths of the intermediate layer and coupling strengths.

2. POWER FLOW EQUATION

Time-independent power flow for multimode SC fibers is described by the following coupled-power equation [13]:

$$\frac{\partial P(\theta,z)}{\partial z} = -\alpha(\theta)P(\theta,z) + \frac{D}{\theta}\frac{\partial}{\partial\theta}\left(\theta\frac{\partial P(\theta,z)}{\partial\theta}\right) \qquad (1)$$

This equation can be written in the following way for

$$\frac{\partial P(\theta,z)}{\partial z} = -\alpha(\theta)P(\theta,z) + \frac{D}{\theta}\frac{\partial P(\theta,z)}{\partial\theta} + D\frac{\partial^2 P(\theta,z)}{\partial\theta^2} \qquad (2)$$

where $P(\theta,z)$ is the angular power distribution at distance z from the input end of the fiber, θ is the propagation angle with respect to the core axis, D is the coupling coefficient assumed constant [15,16] and $\alpha(\theta) = \alpha_0 + \alpha_d(\theta)$ is the modal attenuation, where α_0 represents conventional losses (absorption and scattering). The term α_0 leads only to a multiplier $\exp(-\alpha_0 z)$ in the solution and is thus neglected. The boundary conditions are $P(\theta_m,z) = 0$, where θ_m is the maximum propagation angle, and $D(\partial P/\partial\theta) = 0$ at $\theta = 0$.
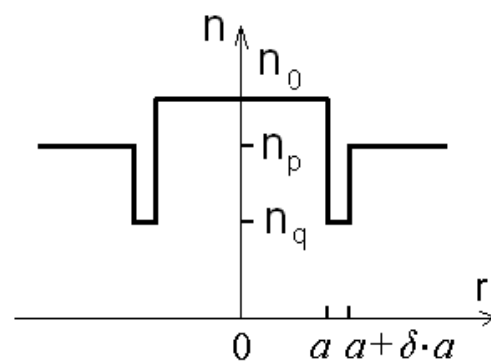

Figure 1. Refractive index profile of a W-type fiber

Consider a W-type fiber with index profile shown in Figure 1. The relative refractive index dif-

ference $\Delta_q = (n_0 - n_q)/n_0$ between the core and intermediate layer is larger than the difference $\Delta_p = (n_0 - n_p)/n_0$ between the core and cladding, where n_0, n_q and n_p are refractive indices of the core, intermediate layer and cladding, respectively. In this

$$\alpha_L(\theta) = \frac{4(\theta^2 - \theta_p^2)^{1/2}}{a(1-\theta^2)^{1/2}} \frac{\theta^2(\theta_q^2 - \theta^2)}{\theta_q^2(\theta_q^2 - \theta_p^2)} \exp\left[-2\delta a n_0 k_0 (\theta_q^2 - \theta^2)^{1/2}\right] \tag{3}$$

where k_0 is the free-space wave number, a is core radius and δa intermediate layer (inner cladding) width. In an SC fiber, experimental results show that attenuation remains constant throughout the guided-mode region and rises quite steeply in the radiation-mode region [18]. Consequently, the modal attenuation in a W-type fiber can be expressed as:

$$\alpha_d(\theta) = \begin{cases} 0 & \theta \leq \theta_p \\ \alpha_L(\theta) & \theta_p < \theta < \theta_q \\ \infty & \theta \geq \theta_q \end{cases} \tag{4}$$

A W-type fiber can be regarded as a system consisting of SC_q fiber and cladding. In the SC_q fiber, modes having propagation angles smaller than the critical angle θ_q can be guided. When the SC_q fiber is coupled with surrounding medium of index n_p, the lower order modes, whose propagation angles are smaller than the critical angle of the SC_p fiber θ_p, remain guided. However, the higher order modes with angles between θ_p and θ_q are transformed into leaky modes. It is shown that because of the strong dependence of $\alpha_L(\theta)$ on the intermediate layer width δa, steady-state characteristics of a W-type fiber depend on δa and coincide with those of SC_p and SC_q fibers in the limits of $\delta\to 0$ and $\delta\to\infty$, respectively [17, 20]. Another parameter which influences the power distribution in W-type optical fibers is a depth of intermediate layer (Figure 1). In this paper, we investigate how the depth and the

structure, the modes whose propagation angles are between $\theta_p \cong (2\Delta_p)^{1/2}$ and $\theta_q \cong (2\Delta_q)^{1/2}$ are leaky modes [16]. Attenuation constants of leaky modes are given as [17]:

width of intermediate layer influence the transient and EMD in W-type glass optical fibers for different strengths of mode coupling and different widths of launch beam distribution. The results obtained could be applied when designing W-type glass optical fibers.

3. NUMERICAL METHOD

Since the analytical solution of the power flow equation (2) with the attenuation constants of leaky modes in the form of (3) is not available, one has to solve it numerically. We have done that for the W-type optical fiber using the explicit finite difference method (EFDM). To start the calculations, we used Gaussian launch-beam distribution of the form:

$$P(\theta, z) = \exp\left[-\frac{(\theta - \theta_0)}{2\sigma_0^2}\right] \tag{5}$$

with $0 \leq \theta \leq \theta_c$, where θ_0 is the mean value of the incidence angle distribution, with the full width at half maximum $(\text{FWHM})_{z=0} = 2\sigma_0\sqrt{2\ln 2} = 2.355\sigma_0$ (σ_0 is a standard deviation of the incidence angle distribution). We used the central difference scheme to represent the $(\partial P(\theta, z))/\partial\theta$ and $(\partial^2 P(\theta, z))/\partial\theta^2$ terms, and the forward difference scheme for the derivative term $(\partial P(\theta, z))/\partial z$ [21]. Then, the equation (2) reads

$$P_{k,l+1} = \left(\frac{\Delta z D}{\Delta\theta^2} - \frac{\Delta z D}{2\theta_k\Delta\theta}\right)P_{k-1,l} + \left(1 - \frac{2\Delta z D}{\Delta\theta^2} - (\alpha_d)_k\Delta z\right)P_{k,l} + \left(\frac{\Delta z D}{2\theta_k\Delta\theta} + \frac{\Delta z D}{\Delta\theta^2}\right)P_{k+1,l} \tag{6}$$

where indexes k and l refer to the discretization step lengths $\Delta\theta$ and Δz for angle θ and length z, respectively, where:

$$(\alpha_d)_k = \begin{cases} 0 & \theta_k \leq \theta_p \\ \dfrac{4(\theta_k^2 - \theta_p^2)^{1/2}}{a(1-\theta_k^2)^{1/2}} \dfrac{\theta_k^2(\theta_q^2 - \theta_k^2)}{\theta_q^2(\theta_q^2 - \theta_p^2)} \exp\left[-2\delta a n_0 k_0 (\theta_q^2 - \theta_k^2)^{1/2}\right] & \theta_p < \theta_k < \theta_q \\ \infty & \theta_k \geq \theta_q \end{cases} \tag{7}$$

In the difference form, boundary conditions become $P_{N,l}=0$ and $P_{0,l}=P_{1,l}$, where $N=\theta_q/\Delta\theta$ is the grid dimension in θ direction. To prevent the problem of singularity at grid points $\theta=0$, we have used the following relation [19]:

$$\lim_{\theta\to0}\frac{1}{\theta}\frac{\partial}{\partial\theta}\left(\theta\frac{\partial P}{\partial\theta}\right)=2\frac{\partial^2 P}{\partial\theta^2}\bigg|_{\theta=0} \qquad (8)$$

In this manner, we could determine the angular power distribution at different lengths of W-type fiber.

4. NUMERICAL RESULTS

In this paper, we analyze spatial transients of power distribution as well as the EMD for the coupling of guided to leaky modes in a W-type glass optical fiber. The fiber structural characteristics were: Δ_p =0.2% ($\theta_p \cong 3.62^o$), Δ_q =0.7% ($\theta_q \cong 6.76^o$) and $2a$=60 μm [16, 20]. Further, n_0 =1.46 and λ=840 nm were used in the calculations. In order to investigate the influence of depth and width of the intermediate layer as well as the coupling strength and the width of launch beam distribution on the power distribution in this fiber, we consider the case when the core index n_0 and outer cladding index n_p are fixed. The depth of the intermediate layer is varied by changing the initial value of $\Delta_q = 0.7\%$ for ±15 and ±25%, thus we analyzed cases where $\Delta_q=$ 0.525% ($\theta_q \cong 5.87^o$), $\Delta_q = 0.595\%$ ($\theta_q \cong 6.25^o$), $\Delta_q \cong 0.7\%$ ($\theta_q \cong 6.76^o$), $\Delta_q = 0.805\%$ ($\theta_q \cong 7.27^o$) and $\Delta_q = 0.875\%$ ($\theta_q \cong 7.58^o$) [22]. The change in θ_q for constant θ_p changes the number of leaky modes as well as their attenuation (3). We solved the power flow equation (2) using EFDM for the coupling coefficient $D = 2.3\times 10^{-7}$, 2.3×10^{-6} and 2.3×10^{-5} rad^2/m and for two different normalized intermediate layer widths δ (δ=0.2 and 0.5; actual widths $\delta\cdot a$ are 0.2·30 μm and 0.5·30 μm). We solved the power flow equation by selecting Gaussian launch-beam distribution with (FWHM)$_{z=0}$=1° and 3° by setting $\sigma = 0.425°$ and 1.274° in equation (5), respectively. The relevant numerical values are summarized in Table 1 to facilitate easier comparisons.

As an illustration, in Figure 2, our numerical solution of the power flow equation is presented by showing the evolution of the normalized output power distribution with fiber length for W-type glass fiber with characteristics Δ_q = 0.7%, δ = 0.2 and $D = 2.3\times10^{-7}$ rad^2/m, for Gaussian launch-beam distribution with (FWHM)$_{z=0}$=1°. We show the results for four different input angles θ_0 = 0, 1.2, 2.4 and 3.6° (measured inside the fiber). Critical angles θ_p and θ_q are also marked in Figure 2.

One can see in Figure 2 that when the launch distribution at the input end of the fiber is centered at θ_0=0, the power distribution remains at the same angle as the distance from the input fiber end increases, but its width increases due to mode coupling. Radiation patterns in Figure 2(a) of non-centrally launched beams in short fibers are centered at values which are close to their initial values. With increasing the fiber length one can observe in Figure 2(b) that coupling is stronger for the low-order modes: their distributions have shifted more towards θ=0°. Coupling of higher-order modes can be observed only after longer fiber lengths (Figure 2(c)). It is not until the fiber's coupling length L_c that all the mode-distributions shift their mid-points to zero degrees (from the initial value of θ_0 at the input fiber end), producing the EMD in Figure 2(d) of L_c = 2400 m.

One can see in Table 1 that with increasing the strength of mode coupling (D), there is a decrease of length L_c which is necessary for achieving the EMD. This is because stronger mode coupling, which is due to larger intrinsic perturbation effects in the fiber, forces energy redistribution among guided modes to occur at shorter fiber lengths. The lengths L_c are shorter for wider launch beam. This is because the energy of a wide launch beam is more uniformly distributed among guided modes in the fiber, forcing the EMD at shorter distances than for a narrow launch beam. With an increasing depth of the intermediate layer, the fiber length L_c at which the EMD is achieved increases. This is explained by the correspondingly increasing number of leaky modes. The larger the number Δ_q (larger Δ_q and consequently θ_q), the longer the fiber length it takes for the coupling process to complete. This increase is more pronounced in the case of narrower intermediate layer width ($\delta = 0.2$). Since leaky mode loss decreases with increasing width of the intermediate layer, power remains in leaky modes for a rather long transmission length in the case of $\delta = 0.5$, which results in longer fiber length which is necessary for achieving the EMD if compared to that of $\delta = 0.2$ case. Similarly, for a fixed value of Δ_q, a decrease of δ from 0.5 to 0.2 results in approximately the same decrease of L_c if compared to the case of changing Δ_q from 0.875 to 0.525% for a fixed value of δ. One can also see that the cou-

pling length L_c of W-type glass fibers (Table 1) varies between those of the reference SC_p and SC_q fiber (Table 2) with the width of the intermediate layer. The shortest coupling lengths characterize SC_p fiber. This is due to the fact that mode coupling occurs only between guided modes which propagate along the fiber with propagating angles θ between 0 and

3.62^o. The longer coupling lengths which characterize SC_q fiber if compared to those of SC_p fiber are due to a larger number of guiding modes which propagate along the SC_q fiber with propagating angles θ between 0 and 6.76^o.

Table 1. W-type glass fiber length L_c at which the EMD is achieved for different values of the coupling coefficient D, intermediate layer width δ, intermediate layer depth Δ_q and width of the launch beam distribution (FWHM)$_{z=0}$.

D (rad^2/m)	δ	Δ_q (%)	L_c (m) ((FWHM)$_{z=0}$ = 1°)	((FWHM)$_{z=0}$ = 3°)
2.3×10^{-7}	0.2	0.525	2090	1720
		0.595	2205	1805
		0.7	2400	1965
		0.805	2690	2230
		0.875	2890	2505
	0.5	0.525	3420	3030
		0.595	3570	3260
		0.7	3660	3430
		0.805	3690	3505
		0.875	3700	3510
2.3×10^{-6}	0.2	0.525	230	188
		0.595	249	204
		0.7	279	233
		0.805	312	269
		0.875	328	290
	0.5	0.525	341	305
		0.595	351	322
		0.7	357	333
		0.805	359	337
		0.875	359	338
2.3×10^{-5}	0.2	0.525	27	22.5
		0.595	29.5	25
		0.7	32.5	28.5
		0.805	34.5	31.5
		0.875	35.5	32.5
	0.5	0.525	34.5	31
		0.595	35.5	32.5
		0.7	36	33.5
		0.805	36	34
		0.875	36	34

We can conclude that L_c is determined by fiber structural parameters, mode coupling strength and width of launch beam distribution. The bandwidth can be improved by reducing the intermediate-layer width, strengthening the mode coupling process or selecting a narrow launch beam distribution [16]. It is evident from Fig. 3 that the steady-state loss changes from that of SC_q to SC_p fiber as the intermediate layer width becomes thin-

ner. Since the mode coupling increase results in an increased steady-state loss (Fig. 3), a trade-off relation between bandwidth and loss has to be considered in practice when designing the optimum W-type index profile. Controlling the intermediate layer width entails a smaller sacrifice in loss than an increase in coupling strength. A narrow launch beam distribution leads to a higher bandwidth at small and intermediate fiber lengths if compared to that of

wide launch beam distribution [16]. A wider launch beam distribution forces bandwidth shift from $1/z$ proportional to $1/z^{1/2}$ proportional curve to occur at shorter fiber lengths (Table 1), which results in

bandwidth improvement at shorter fiber lengths. At a certain fiber length where steady-state modal distribution is achieved, the bandwidth converges to a launch independent behavior.
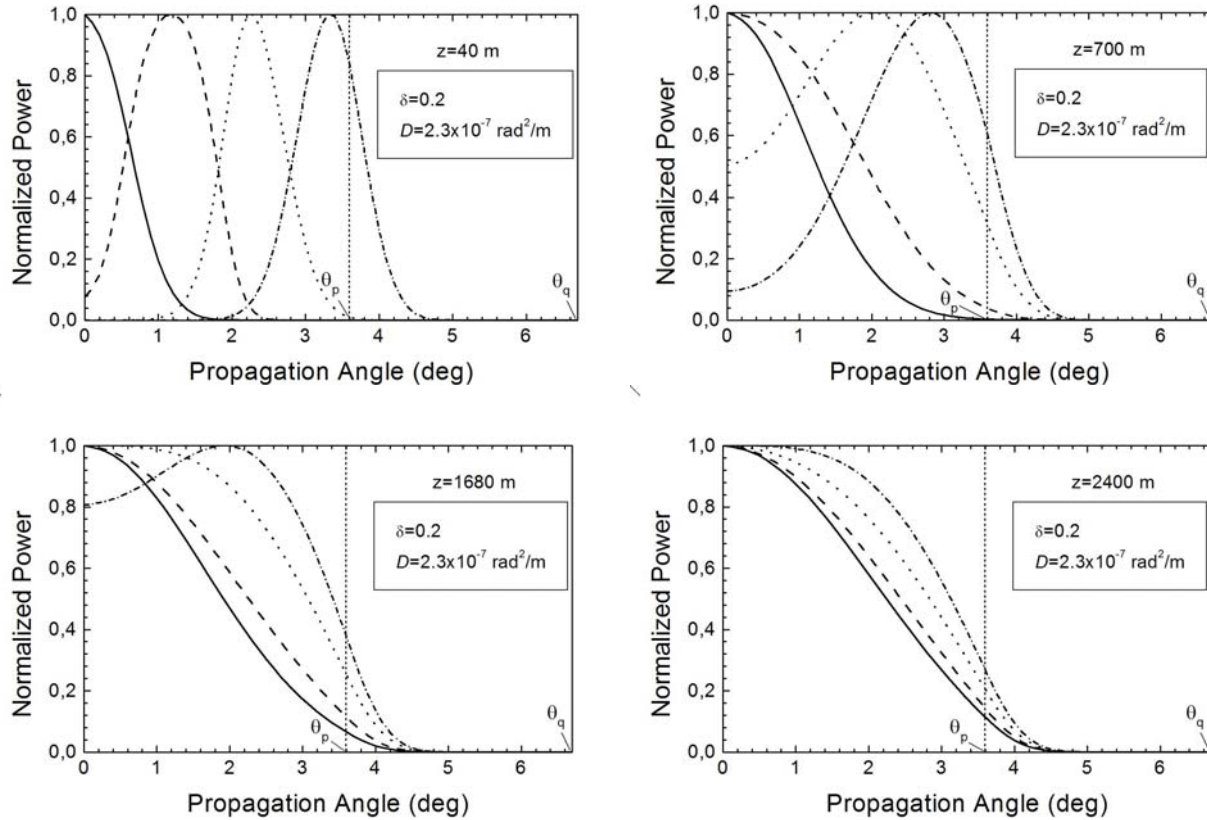

Figure 2. Normalized output angular power distribution at different locations along W-type glass optical fiber calculated for four Gaussian input angles $\theta_0=0°$ (solid curve), 1.2° (dashed curve), 2.4° (dotted curve) and 3.6° (dotted-dashed curve) with (FWHM)$_{z=0}$ =1° for (a) z = 40 m, (b) z = 700 m, (c) z = 1680 m and (d) z = 2400 m. The fiber characteristics are Δ_q = 0.7%, δ = 0.2 and D = 2.3×10^{-7} rad^2/m.

Table 2. SC$_p$ and SC$_q$ fiber length L_c at which the EMD is achieved for different values of the coupling coefficient D and width of the launch beam distribution (FWHM)$_{z=0}$.

	SC$_p$ fiber		SC$_q$ fiber (Δ_q = 0.7%)	
	L_c (m)		L_c (m)	
D (rad^2/m)	((FWHM)$_{z=0}$ = 1°)	(FWHM)$_{z=0}$ = 3°)	((FWHM)$_{z=0}$=1°)	((FWHM)$_{z=0}$= 3°)
2.3×10^{-7}	1880	1560	6600	6100
2.3×10^{-6}	202	157	650	610
2.3×10^{-5}	19	16	65	61

Finally, one should mention here that a similar approach has already been applied to photonic crystal fibers [23]. A large mode area Yb-doped rod-type photonic crystal fiber design with a low refractive index ring in the core is proposed in ref. [23] to provide an improved suppression of the first higher-order mode compared to the case of uniform core

doping, in a way which is more robust against fluctuations in the refractive index value. Results have demonstrated the effectiveness of the low refractive index ring in suppressing the higher-order mode, thus providing an effectively single-mode behavior for the rod-type fibers.
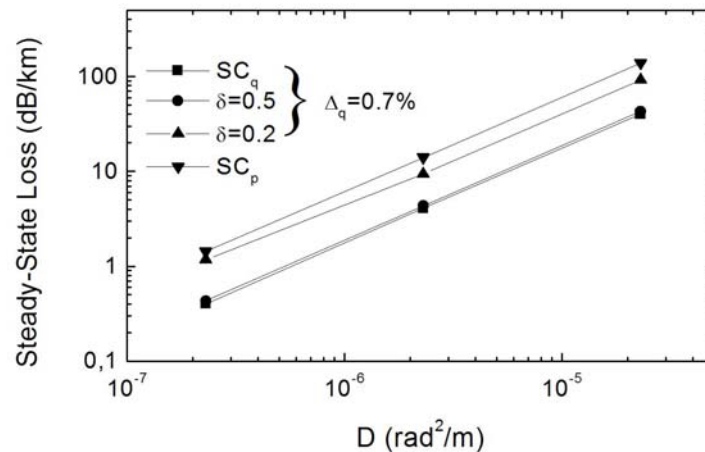
Figure 3. Dependence of steady-state loss on mode coupling strength. (Lines are drawn for visual aid.)

5. CONCLUSION

We have shown how the width of the launch beam distribution influences the coupling length for achieving the equilibrium mode distribution in W-type glass optical fibers for various depths and widths of the intermediate layer and coupling strengths. It is shown that the wider the launch beam, the shorter the length L_c necessary to achieve the EMD in W-type glass fiber. This is because the energy of a wide launch beam is more uniformly distributed among guided modes in the fiber, forcing the EMD at shorter distances than for a narrow launch beam. It is similarly shown that the stronger the mode coupling, the shorter the W-type fiber it takes for the power distribution to reach its modal equilibrium. Since leaky mode loss decreases with an increasing width of the intermediate layer, power remains in leaky modes for a rather long transmission length in the case of $\delta = 0.5$, resulting in longer fiber length which is necessary for achieving the EMD if compared to that of $\delta = 0.2$ case. It is found that the deeper the intermediate layer, the longer the length L_c it takes to achieve the EMD. This is explained by the correspondingly increasing number of leaky modes. The bandwidth can be improved by reducing the intermediate-layer width, strengthening the mode coupling process or selecting a narrow launch beam distribution. In practice a trade-off relation between bandwidth and loss has to be considered in designing the optimum W-type index profile. Controlling the intermediate layer width entails a smaller sacrifice in loss compared to an increase in coupling strength. A narrow launch beam distribution leads to a higher bandwidth at small and intermediate fiber lengths if compared to that of wide launch beam distribution. A wider launch beam distribution forces bandwidth shift from $1/z$ proportional to $1/z^{1/2}$ proportional curve to occur at shorter fiber lengths, which results in bandwidth improvement at shorter fiber lengths.

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РАВНОТЕЖНА РАСПОДЈЕЛА МОДОВА У СТАКЛЕНИМ ОПТИЧКИМ ВЛАКНИМА СА W-ИНДЕКСОМ ПРЕЛАМАЊА

Сажетак: Користећи једначину протока снаге одређена је равнотежна расподела модова у стакленим оптичким влакнима са W-индексом преламања. Показано је како дужина спрезања на којој настаје равнотежна расподела модова у овим влакнима зависи од дубине и ширине средњег слоја влакна, и јачине спрезања модова за различите ширине улазног снопа свјетлости. Оптичка влакна са W-индексом преламања ефикасно смањују модалну дисперзију и губитке усљед савијања влакна.

Кључне ријечи: Стаклена оптичка влакна са W-индексом преламања, спрезање модова.

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