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광섬유 다중통신을 위한 Angular Division Multiplexing

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Angular Division Multiplexing for Multichannel Communication in a Single Fiber

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Angular Division Multiplexing(ADM) is an optical multiplexing technique that offers an important option for attaining multichannel transmission in a relatively short fiber. The angular dependence of the outgoing flux and the temporal impulse response are calculated for round fiber in terms of the fiber's length and the exitation condition

1. Introduction

Local area networks, industrial control systems, and many other fiber applications require transmission of two or more channels of information on a single fiber. ADM is an optical multiplexing technique. ADM uses the differential excitation and detection of groups of modes to trasmit simultaneously several signals in a step-index multimode fiber. Each group is characterized by a set of plane waves propagaating at a specific angle in the fiber.[1] This technique relies on the preservation of a plane wave's axial angle when it is reflected at the core-cladding interface of an ideal step-index fiber.

In addition to multiplexing several channels onto the fiber,ADM can be used to increase the bandwidth of each channel. The differential excitation and detection of modal groups in an ADM system minimizes intermodal dispersion. Each channel will have fewer modes than would ordinarily be propagated in a step-index fiber. The pulse dispersion is,therefore,considerably less than would occur in a fully excited step-index fiber where all the modes are propagated and detected as a single channel. The resultant bandwidth for each channel of the ADM system approaches that of good graded-index fiber.

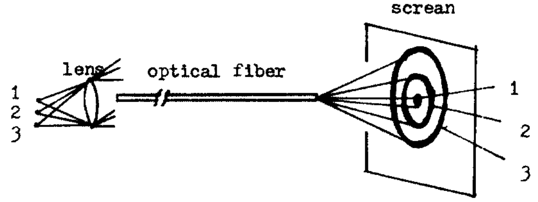

Fig.1 Selective excitation and propagation of four optical channels in a single step-index fiber.

The number of channels,the crosstalk, and the pulse dispersion in an ADM system depend on the amount of coupling between the modes in the fiber. Mode coupling is a function of core-cladding interface roughness, refractive index nonuniformity, and microbending effects caused by cabling the fiber.[2] This power coupling between modes increases with distance. As a result, the distance over which ADM may be employed to provide multichannel transmission with increased bandwidth is currently limited to one kilometer for practical step-index fibers.

In this paper we separate the time dependent relation into two equations. First,we exploit Gloge's time indent power-flow equation.[2] Then we include the time-dependence by assuming an average time of flight for each axial angle,and derive a second equation for the change of the average flight-time in each angle as a function of distance.

2. Theory

To find the impulse response and to evaluate the crosstalk levels of a waveguide, we must first calculate the angular distribution of light flux.

An analysis of the length dependence of mode coupling in step-index fiber is based upon the coupled power equations describing the change of power, dp_m of mode m with distance. This change is the result of theloss of power to the radiation modes and copling of power to and from other guided modes, as expressed by

$$\frac{dp_m}{dz} = -\alpha_m p_m + \sum_{n=1}^{M} d_{mn}(p_n - p_m) \qquad \ldots.(1)$$

where m is the compound mode number of a group of 2m degenerate modes,and p_m is the power of each of these modes. M is the maximum number of modal groups, α_m is loss constant of mode m, and d_{mn} is the coupling coefficient between modes.

For a practical multimode fiber fiber,as used in an ADM system, coupling is assumed to occur primarily between nearest neighbors. Therefore, power coupled between modes may be described by a diffusion-type diffrential equation:

$$\frac{dp(\theta,z)}{dz} = -A\theta^2 p(\theta,z) + \frac{1}{\theta}\frac{\partial}{\partial\theta}\left(\theta d(\theta)\frac{\partial p(\theta,z)}{\partial\theta}\right) \quad \ldots(2)$$

where θ is the axial angle that replaces the mode number m and $d(\theta)$ is the coupling coefficient.

By the technique of the separation of the variables, the angular power distribution is (plane wave input)[4]

$$p(x,z) = \exp\left(-\left(\frac{x_0 + x}{2}\right)\left(\frac{1+\exp(-bz)}{1-\exp(-bz)}\right)\right) \quad \ldots(3)$$

$$\cdot\left(\frac{\exp(-1/2bz)}{1-\exp(-bz)}\right) I_0\left(\frac{(4x_0 x)^{1/2}\exp(-1/2bz)}{1-\exp(-bz)}\right)$$

where $x = (A/D)^{1/2}\theta^2$, $b = 4(AD)^{1/2}$

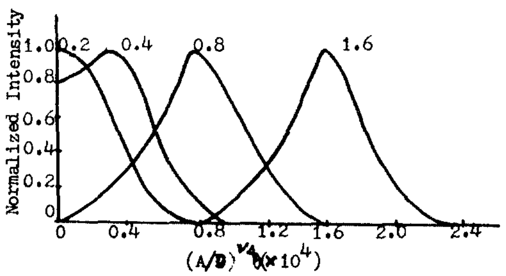

Fig.2 Normalized output angular power distribution for the normalized input angles at a fixed fiber length.

If we place a detecter of angular width $2\Delta_d$ to detect the light from channel i, then the signal is

$$Si(z) = \int_{\theta_m^i - \Delta d}^{\theta_m^i + \Delta d} p_i(\theta,z)\,d\theta \qquad \ldots.(4)$$

where θ_m^i is the angle in which the function is maximum. The crosstalk is

$$\text{Crosstalk} = 10 \log \sum_{j \neq i}^{N} \frac{S_j}{Si} \qquad \ldots.(5)$$

Knowing the angular distribution at any given distance,we can priceed to find the temporal reponse by introducing "average-time"model. Consider a photon propagating in track q with a known velocity

$$v_q = v_0 \cos\theta_q \qquad \ldots.(6)$$

where v_0 is the velocity of a ray along the core axis. After a certain distance,the ray scatters to a neighboring track q + 1,propagate a certain distance with the new velocity and rescatters. By knowing the probabilties of all possible paths,it is possible to find the impulse response exactly,but calculation of these countless number of probabilities is difficult. To overcome this problem, we replace all photons in a given track by a "composite" photon whose time of flight to the distance z is the average flight time of the photons in the track. At the distance $z + \Delta z$ the average time $\bar{t}_q$ at track q is changed mainly by adding the flight time $\Delta z/v_q$ plus minor corrections due to interaction with neighboring tracks. The recursive equation for the average time would therefore be

$$\bar{t}_{q,n+1} = \frac{1}{E_{q,n}}\Big\{(\bar{t}E)_{q,n}\left(1-d_q-\left(\frac{q-1}{q}\right)d_{q-1}\right) + (\bar{t}E)_{q+1,n}\left(\frac{q}{q+1}\right)d_q + (\bar{t}E)_{q-1,n}d_{q-1}\Big\}$$

$$+\frac{z}{v_q} \qquad \ldots.(7)$$

where we have the condition

$$t_{q,0} = 0 \qquad \ldots.(8)$$

Equations(7),(8) form the basis for numerically solving the round fiber. Inthe multimode approximation they can be transformed into partial differential equations. Thus we obtain

$$\frac{\partial}{\partial z}(p(\theta,z)\bar{t}(\theta,z)) = \frac{D}{\theta}\frac{\partial}{\partial\theta}\left(\theta\frac{\partial}{\partial\theta}(p(\theta,z)\bar{t}(\theta,z))\right) + \frac{p(\theta,z)}{v(\theta)} \ldots(9)$$

The analytic solution of above equation is difficult, but for off-axis excitation, the equation is similar to the slab waveguide. The on-axis excitation problem was considered elsewhere.[3] For the slabwaveguide, assuming that the coupling coefficient is indepedent of angle, we obtain in mutimode approximation

$$\frac{\partial}{\partial z}(p(\theta,z)\bar{t}(\theta,z)) = D\frac{\partial^2}{\partial\theta^2}(p(\theta,z)\bar{t}(\theta,z)) + \frac{p(\theta,z)}{v(\theta)} \quad \ldots(10)$$

$$\bar{t}(\theta,0)=0 \quad \ldots.(11)$$

The solving procesure is cumbersome, but bacause our interest is confined to short distances, it can be alleviated with certain approximation. First, let p be the basic Gaussian form

$$p(\theta,z)=\frac{1}{\sqrt{\pi}(4Dz+\sigma_0^2)^{1/2}}\exp\left(-\frac{(\theta-\theta_0)^2}{4Dz+\sigma_0^2}\right) \quad \ldots.(12)$$

and finally approximate the velocity for small angle $1/v(\theta) = (1+\theta^2/2)/v_0$. Then we obtain the solution

$$\bar{t}(\theta,z)=\frac{z}{v_0}+\frac{z}{v_0}\frac{2D}{\tau^4}\Big((\tau^2+2\theta\theta_0)(\frac{1}{6}z^2+\frac{1}{2}z\frac{\sigma_0^2}{4D}) + \theta^2(\frac{1}{3}z^2+\frac{1}{2}z\frac{\sigma_0^2}{2D}+\frac{1}{4}\frac{\sigma_0^2}{4D^2})+\theta_0^2\frac{1}{3}z^2\Big) \quad \ldots.(13)$$

where $\tau^2 \equiv 2Dz+\sigma_0^2/2$. For plane-wave excitation, i.e., for $\sigma_0 \to 0$, expression (13) is simplified to

$$\bar{t}(\theta,z)=\frac{z}{v_0}(1+\frac{1}{6}(Dz+\theta\theta_0+\theta^2+\theta_0^2));\ \sigma_0=0 \quad \ldots.(14)$$

Note two interesting facts. First, the average time depends on the excitation angles θ_0. Second the average flight time in the track $\theta=\theta_0$ is, in the presence of coupling, longer than the regular flight time in that track. Equation(14) shows that when $Dz<\theta_0^2$, the average time in a track a track $\theta<\theta_0$ is longer than the flight time in that track, but in track in track $\theta>\theta_0$ the average time is shorter than the flight time.

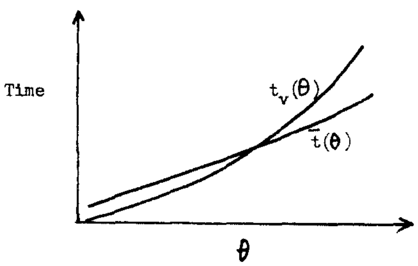

Fig.3 The "average time" $\bar{t}(\theta)$ in every track-θ. For comparison, the regular flight time $t_v(\theta)$ is also shown

From (12),(13), we can calculate approximately the average arrival time of a short input pulse-$\langle\bar{t}(z)\rangle$ and the temporal width of the output pulse-$\sigma_t(z)$

$$\langle\bar{t}(z)\rangle=\int_{-\infty}^{\infty}\bar{t}(\theta,z)p(\theta,z)d\theta$$

$$\sigma_t(z)=\int_{-\infty}^{\infty}(\bar{t}(\theta,z)-\langle\bar{t}(z)\rangle)^2p(\theta,z)d\theta \quad \ldots.(15)$$

The expression for $\langle\bar{t}(z)\rangle$ can be obtained directly from (13) after the following substitutions are made: $\theta\to\langle\theta\rangle=\theta_0$, and $\theta^2\to\langle\theta^2\rangle=\sigma^2+\theta_0^2$. The rms pulse width σ_t is evaluated to yield

$$\sigma_t(z,\sigma_0,\theta_0)=\frac{z}{v}\frac{2D}{\tau^4}(V^2+4VW\theta_0+W^2(2\tau^2+4\theta_0^2))^{1/2}$$

$$V\equiv(\frac{1}{3}z^2+z\frac{\sigma_0^2}{4D})\theta_0 \quad \ldots.(16)$$

$$W\equiv\frac{1}{3}z^2+\frac{1}{2}z\frac{\sigma_0^2}{2D}+\frac{1}{4}\frac{\sigma_0^2}{4D^2}$$

$$\tau^2\equiv 2Dz+\frac{1}{2}\sigma_0^2$$

In (16), the rms pulse width is given as a fuction of length z, and two parameters of the exciting Gaussian beam - the angular width σ_0 and the obliquity θ_0.

For the plane-wave excitation, the pulse width becomes

$$\sigma_t(z)=\frac{1}{\sqrt{2}}\frac{z}{v_0}(Dz)^{1/2}\theta_0(1+\frac{4}{9}\frac{Dz}{\theta_0^2})^{1/2};\quad \sigma_0=0 \quad ..(17)$$

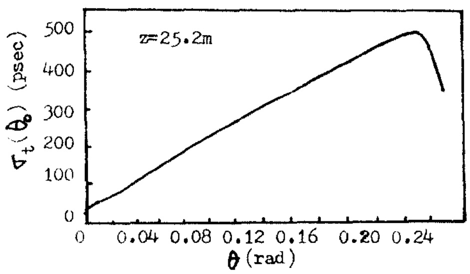

Fig.4 Dependence of pulse width on the axial angle of the exciting plane wave

Equation(17) and Fig.4 show that in case of angular multiplexing, the bandwidth is greater for channels with small angular orientation than for channals with higher angular orientation.

We consider on-axis excitation for which the pulse width becomes

$$\sigma_t(z)=\sqrt{2}\frac{z}{v_0}\frac{(\sigma_0/2)^4+(\sigma_0/2)^2Dz+\frac{1}{3}(Dz)^2}{Dz+(\sigma_0/2)^2};\ \theta_0=0 \ldots(18)$$

(18) may be simplified further to

$$\sigma_t(Dz \ll \sigma_0^2) = \frac{1}{\sqrt{2}} \cdot \frac{1}{2} \frac{z}{v_0} \sigma_0^2 \qquad \cdots\cdots(19)$$

$$\sigma_t(Dz \gg \sigma_0^2) = \frac{\sqrt{2}}{3} \cdot \frac{z}{v_0}(Dz) \qquad \cdots\cdots(20)$$

(19) shows that the temporal pulse width is very sensitive to the angular width of the exciting beam ;as the angular divergence decreases the pulse width becomes narrower. On the other hand,(20) shows that for very small divergence (as in ADM), the pulse width is proportional to the distance to the second power,so that for low crosstalk level as well as high information rates,short distances are essential.

Now we reenter the round optical fiber. The result of our numerical calculation of (7) and (8) are shown in Fig.5 and Fig.6. Fig.5 shows the impulse response of a round fiber calculated in accordance to the time average model for several input angles of plane-wave excitation. The bandwidth of channels decreases as their angular distance from the symmetry axis increase.

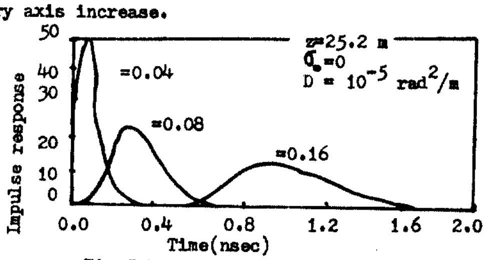

Fig.5 Temporal impulse response of a round fiber. In ADM, each channel have a different bandwidth.

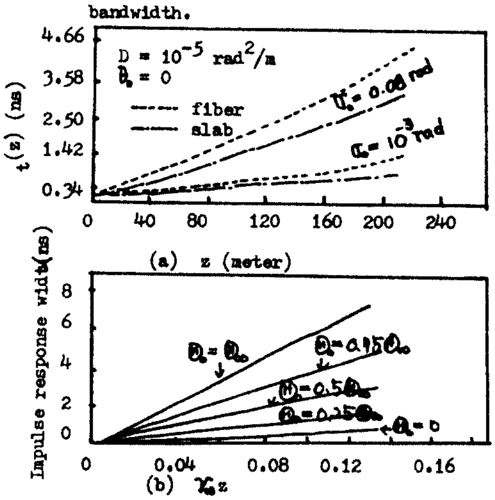

Fig.6 Pulsewidth as a function of distance

(a) Calculated according to the "average-time"

(b) Calculated from Gloge'equation

Fig.(6) shows the pulsewidth $\sigma_t(z)$ for a slab waveguide(dashed curve) and for a round fiber(solid curve). The pulsewidth calculated according to Gloge's equation is given. For shortfibers,the pulsewidth depends strongly on the angular width of the excitation beam,and this fact is the feature of ADM.

3. Conclusion

ADM offers great advantage for multichannel communication in a single fiber. ADM have several channels and increase the the bandwidth of each channel.

Temporal width decreases significantly as the angular width of the exciting beam decrease,and this is the main reason for the large bandwidth that can be achieved by ADM.

But ADM has some limitations such as fiber length (about 1 km),and the number of channels.

The theoretical and numerical calculation show the limitations and advatages of increasing the rate of information transmission through optical waveguides by angular multiplexing of several channels

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