Using Higher-Order Passbands of Multimode Fibre for Subcarrier Multiplexing

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The frequency response of multimode optical fibre (MMF) shows the existence of passbands in the higher frequency region above the -3dB baseband. By Subcarrier Multiplexing, these passbands can be used to accommodate a number of transmission channels for different services. In this way various groups of services may be integrated in a single MMF-based in-building or short-reach access infrastructure. In this paper, the power flow equation is solved numerically to investigate the passband response of MMF. The influence of modal delay, modal attenuation, mode coupling and launching conditions is studied. Results show large differences between overfilled launching and selective excitation launching.

Introduction

As an access network architecture, Fibre-to-the-Home (FTTH) is the most powerful and future-proof technique for providing broadband services to residential users. Up to now, single mode optical fibre (SMF) dominates the deployed FTTH systems, due to its huge bandwidth and hence tremendous signal transport capacity. However, installation of single mode fibre requires great care, delicate high-precision equipment and highly skilled personnel, which makes installation costly and thus prevents large-scale introduction of FTTH. As an alternative medium, multimode optical fibre (MMF) has been attracting much interest. A clear drawback of MMF is that the modal bandwidth limits the transmission distance [1]. To overcome this limitation, the Subcarrier Multiplexing (SCM) technique has been proposed based on the passbands at higher frequencies of the MMF [2] [3]. The passband characteristic is influenced by several factors, such as fibre core size, refractive index profile and launching condition [4]. In this paper, we investigate the frequency response of 50/125 μm silica MMF under different conditions by solving power flow equations numerically. Simulation results indicate the frequency bands available for SCM applications.

Theory

Graded index MMFs (GI-MMF) which are widely used nowadays have a power-law index profile defined as

$$n(r)=\begin{cases} n_1\sqrt{1-2\Delta(r/a)^{\alpha}}, & \text{for } 0\le r\le a \\ n_2, & \text{for } r\ge a \end{cases} \qquad (1)$$

where n_1 and n_2 are the refractive indices at the fibre core centre and the cladding, respectively, r is the offset distance from the fibre core centre, a is the fibre core radius. Δ is the fractional index change at the core-cladding interface. The index exponent α determines the index profile: α=2 corresponds to a parabolic profile while α=∞ results in a step-index profile. MMF with this index profile supports many mode groups. Each group contains a number of modes propagating at same speed, which is determined by the corresponding propagation constant β [4] [5],

$$\beta(m,\lambda) = 2\pi \frac{n_1}{\lambda}\sqrt{1-2\Delta(m/M)^{2\alpha/(\alpha+2)}} \qquad (2)$$

where λ is the wavelength in vacuum, m is the order of mode group and M is the total number of mode groups that can be guided in the fibre. The transfer function of an MMF can be modeled by the product of two filter functions, which describe the chromatic and modal dispersion [4]. The difference between propagation speeds is the major contribution to the modal dispersion. However, within the reach of an access network, fibre link length is normally only a few kilometers. In this scenario, chromatic dispersion is much smaller than modal dispersion and thus can be ignored. With this assumption, the frequency response of MMF is approximated by the modal transfer function, as given in [4],

$$H(\lambda_0, z, \omega) = \int_{x_0}^{1} 2xR(x, \lambda_0, z, \omega)dx \qquad (3)$$

where $x=m/M(\lambda_0)$is the normalized mode group number and $x_0=1/ M(\lambda_0)$; z is the distance from the beginning of the fibre along the fibre axis. In this equation, function $R(x,\lambda_0,z,\omega)$ is the modal power in the frequency domain, which incorporates the effect of modal excitation efficiency, modal delay, modal attenuation and mode coupling. This power flow is described by the following partial differential equation [4]

$$\frac{\partial R(x,\lambda_0,z,\omega)}{\partial z} = -[i\omega\tau(x,\lambda_0) + \gamma(x,\lambda_0)]R(x,\lambda_0,z,\omega) + \frac{1}{x}\frac{\partial}{\partial x}[xd(x,\lambda_0)\frac{\partial R(x,\lambda_0,z,\omega)}{\partial x}] \qquad (4)$$

where $\tau(x,\lambda_0)$, $\gamma(x,\lambda_0)$ and $d(x,\lambda_0)$ are mode-dependent parameters: the modal delay per unit length, the modal attenuation (in the absence of mode coupling effect) and the mode coupling coefficient. Normally there is no simple analytical solution of Eq. (4) and the power flow function R can only be obtained using a numerical procedure. For this purpose, the Crank-Nicholson scheme is used in this research. Furthermore, appropriate boundary and initial conditions should also be imposed. Once R is obtained by solving Eq. (4), it can be inserted into Eq. (3) to calculate the frequency response as $10\log_{10}(|H(\lambda_0,z,\omega|)$.

Results

First, we analyzed the frequency response of 50/125 μm graded index silica MMFs with length of 2000 meters. The numerical aperture is about 0.2 at a wavelength of 1300 nm. To investigate the influence of the index exponent α of the exponential refractive index profile, three different values 1.8, 2.0 and 2.2 are taken. The refractive indices at the core centre and the cladding are n_1=1.4465 and n_2=1.4326. A laser source at a wavelength 1300 nm and with a root mean square (RMS) spectral width of 3 nm was used. Since modal delay (MD) is the main contribution to the frequency response in short reach MMF links, it was included in all simulations. The effect of index exponent α, differential mode attenuation (DMA) and mode coupling (MC) were investigated separately.

Fig. 1 reports the frequency responses with the three α values. As indicated by this figure, the index exponent has great impact on frequency response. For α=2, the -3 dB bandwidth is around 1.85 GHz and the curve does not drop monotonously from the zero-frequency value but exhibits first two sidelobes with peak frequencies located at

4.3 GHz and 7.3 GHz. Although there is about 7 to 10 dB attenuation compared to baseband level, these two side lobes can provide 2.05 GHz and 2.4 GHz bandwidths and thus allow for the transmission of passband channels using subcarrier multiplexing. Similar results were also obtained in our previous research in which a relative simple model was used [6]. However, when the index profile deviates from the parabolic shape (here α =1.8 and 2.2), the -3dB bandwidth decreases sharply to about 200 MHz. Moreover, the level drops quickly above the -3 dB region and no side lobes could be observed as in the case when α =2.

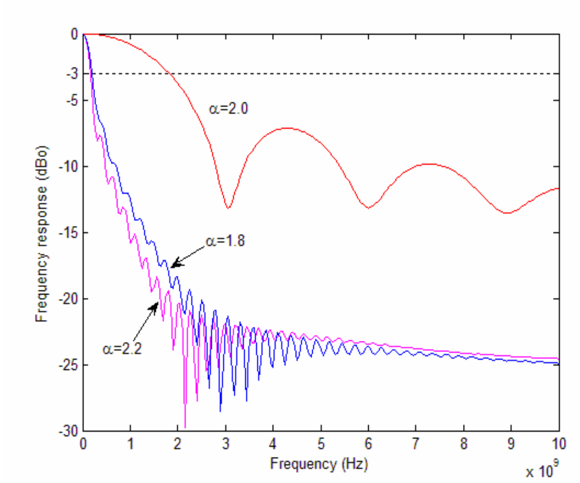

Figure 1. Frequency responses for a 2000-m-long fibre with λ_0=1300 nm and index exponent α =1.8 2.0 and 2.2. The mode delay, differential mode attenuation and mode coupling are all included.

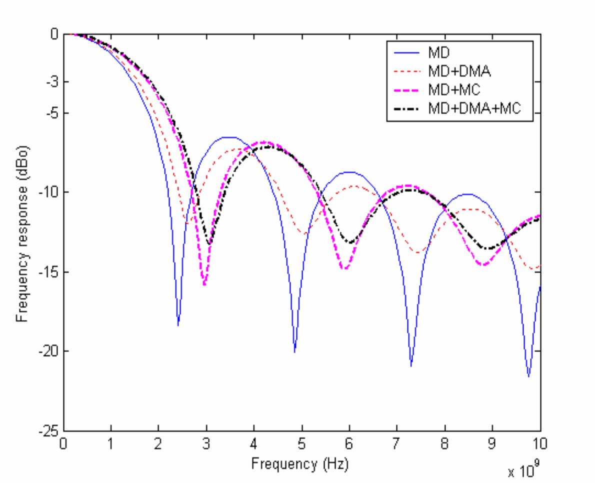

Figure 2. Influence of the differential mode attenuation and mode coupling. The index exponent α =2.0. Other parameters are the same as used in Fig. 1. MD: modal delay, MC: mode coupling, DMA: differential mode attenuation.

Frequency responses displayed in Fig. 2 show the influence of DMA and MC. The index exponent is 2.0 and will be maintained for all subsequent simulations. Although either DMA or MC has little effect on the -3 dB bandwidth of this fibre, higher-order passbands exist in all cases with different combinations of the 3 mode dependent parameters. The amplitude and position of these passbands change when DMA and/or MC are taken into account and MC contributes more to the change than DMA does.

Secondly, selective excitation was simulated for a silica MMF of 750 m length. Except the length, all the other parameters were kept the same as in above simulation. With these parameters, totally 12 mode groups can potentially propagate in this fibre. To investigate the effect of selective launching, different subsets of mode groups were excited. Results presented in Fig. 3 indicate clearly that the largest -3dB bandwidth is reached when lower order mode groups propagate along the fibre (e.g. group 1-5 excited). With the increase of the order of the guided mode groups, the -3 dB bandwidth decreases and passbands appear in the frequency region concerned. As a comparison, the response under overfilled launching (all 12 mode groups were excited) is also shown in this figure. Also measurements have been done, of which the results are shown in Fig. 4; these show qualitatively a similar variation trend. With butt coupling light from SMF into a 50/125 μm GIMMF, only lower order mode groups were excited. Higher order mode groups were excited by offsetting fibre axes of the SMF and MMF along the radial direction of the fibre end surface. However, an accurate relationship between the offset distance and excited mode groups needs further investigation.

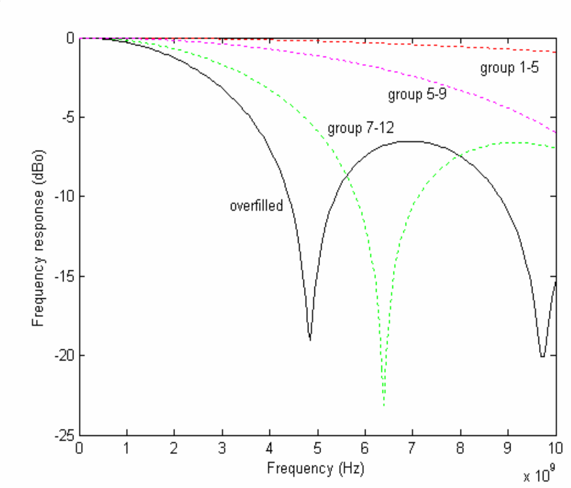

Figure 3. Frequency responses with different mode groups excited

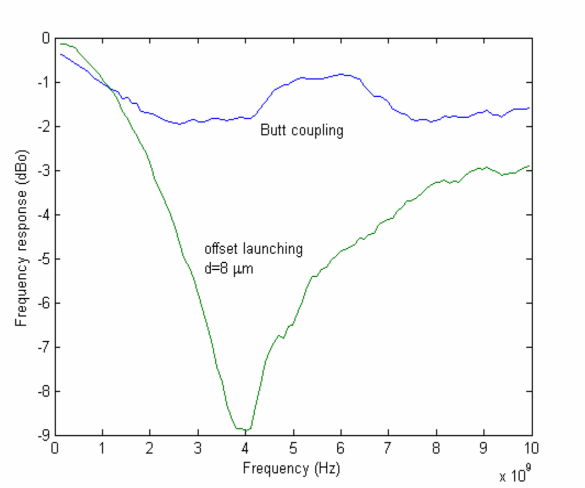

Figure 4. Measured frequency response of a 50/125 µm GIMMF, L=750m.

Conclusions

The frequency response of GI-MMF is investigated numerically. The index exponent and launching conditions have large effect on the higher-order passband characteristics. To apply SCM over MMF, subcarrier frequencies should be allocated carefully to the higher-order passbands, preferably by adjusting them adaptively to the fibre's characteristics.

Acknowledgement

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