

Passband Characteristic of MM Fibers

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Received June 8, 2009; accepted June 23, 2009; published June 30, 2009

Abstract—Frequency response of Multimode (MM) fibers beyond the baseband is studied. It is shown that in the absence of mode group mixing there are relative flat passbands suitable for transmission in such fibers if the number of mode groups propagating is not too large. Such conditions are usually met for typical contemporary graded index (GI) silica fibers. It is also proved that the passbands width is related to the baseband width. Moreover, a 1300 nm window is the most suitable for transmission due to small chromatic dispersion and reduced number of mode groups propagating.

Multimode (MM) fiber is often used as a transmission medium for short distances in networks such as LANs. The primary problem when applying such a fiber is its limited bandwidth, which makes it difficult to obtain high informational throughput and upgrade existing systems to higher bit rates (such as 10 Gbit/s Ethernet). There were proposed several techniques to release this limitation, such as electrical equalization [1], mode group multiplexing [2], a special fiber for modal dispersion compensation [3], application of the subcarrier multiplexing (SCM) technique [4,5], etc. The latter solution is based on the fact that the frequency response of certain MM fibers does not decrease monotonically outside the baseband. On the contrary, beyond the baseband there are observed relatively flat frequency ranges suitable for SCM transmission [4,5]. Several transmission experiments based on this behavior have been reported so far [4,5]. However, this solution lacks a systematic approach as to the selection of fibers, wavelengths and light launches necessary to make SCM transmission possible. The current paper tries to answer these questions.

Let us consider the frequency response of multimode (MM) fiber. As everybody knows it is determined by two effects, namely chromatic and (inter)modal dispersions. The frequency response, $H(f)$, may be approximated by [6-7]

$$H(f) = \exp\left[-\frac{(2\pi f D L \sigma_\lambda)^2}{2}\right] \cdot \sum_{k=1}^K P_k \exp(-j2\pi f \tau_k L) \cdot 10^{-\alpha_k L/10} \quad (1)$$

Here, f is the frequency, D [ps/nm·km] is the dispersion coefficient, L is the fiber length in km, σ_λ - rms laser linewidth in nm, P_k - the input power of the k -th mode

group, K - is the total number of mode groups, τ_k is the group delay of the k -th mode group, and α_k - the respective attenuation in dB/km. The first factor in (1) is related to chromatic dispersion, whereas the sum represents modal dispersion. It was assumed in (1) that σ_λ takes into account the effects related to laser modulation (chirp) [6].

The total number of modal groups that may propagate in MM fiber depends on its profile parameter g (for a parabolic profile $g=2$), the core diameter D , its numerical aperture NA , and the wavelength λ . The greater the NA , and D , and smaller the wavelength, the more mode groups may propagate in the fiber. For typical GI (graded index) fibers the number of mode groups is 10... 20 for 50 μm core fibers, and 20...30 for 62.5 μm core fibers, whereas the upper limit corresponds to 850 nm, and the lower limit to 1300 nm. The actual number of mode groups propagating in the fiber may be much smaller than the above values for the so called restricted launches when only few mode groups from the entire set are excited at the fiber input.

For regular profile parameters the value of τ_k may be approximated by the formula given in [8,9]. In [10], this formula was compared against the exact (numerical) results. It follows from this comparison that τ_k may be well approximated with a linear relation of the type $\tau_k = k\tau_0$, where τ_0 is the group delay difference between adjacent mode groups. Let us neglect for the moment chromatic dispersion, and assume that N equally excited adjacent mode groups reach the receiver. Inserting the linear expression for τ_k into (1) we get

$$\frac{|H(f)|}{|H(0)|} = \frac{1}{N} \left| \sum_{k=1}^N \exp(-j2\pi f k \tau_0 L) \right| = \frac{1}{N} \left| \frac{\sin(\pi N F)}{\sin(\pi F)} \right| \quad (2)$$

where $F = f\tau_0 L$.

However, greatly simplified eqn. (2) gives a good insight into the MM fiber frequency response outside the baseband. In Fig. 1, the function

$$A(f) = 10 \log_{10} \left| \frac{H(f)}{H(0)} \right| \quad [dB] \quad (3)$$

was shown for the argument $F = f\tau_0 L$ and different values of the number of excited mode groups N .

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Analyzing (3) and observing the curves in Fig. 1 one may readily draw the following conclusions:

a) bandwidths of the passbands beyond the baseband are exactly equal to the baseband except for the passbands located around the multiples of the frequency $f=1/(\tau_0 L)$, which are twice as wide as the baseband,

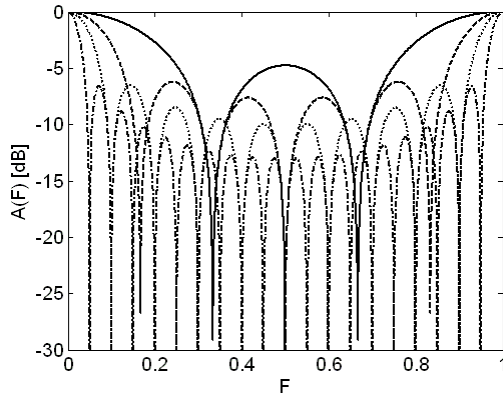


Figure 1. MM fiber frequency response according to (2), (3) versus the parameter $F=f\tau_0 L$ for the following number of mode groups: N=3 (solid line), N=6 (dashed line), N=10 (dotted line), and N=20 (dashed/dotted line)

b) for a given fiber and excitation, an increase in the fiber length causes the decreasing of the baseband and consequently, the passbands widths reduction as well as decreasing of their central frequencies,

c) the fewer mode groups propagate in the fiber (the smaller N) the lesser is the attenuation of the frequency response over the passbands as compared to the attenuation for $f=0$, again with the exception of the passbands located around the multiples of the frequency $f=1/(\tau_0 L)$ where the attenuation (at least theoretically) is the same as the attenuation for $f=0$,

d) the fewer mode groups propagate in the fiber the greater the baseband is (and consequently the passbands),
 e) the least attenuated passband has the central frequency which is smaller if fewer mode groups propagate in the fiber.

The above analysis is performed under rather simplified conditions. Now, we are going to take into account chromatic dispersion as well as the fact that the powers in mode groups reaching the receiver are rarely equal.

Chromatic dispersion is represented by the first factor in eqn. (1), which from now on is included in our calculus. In the sequel, we shall assume the following typical parameters [7]: for 850 nm $D=-10$ ps/(nm·km), $\sigma_\lambda=0,35$ nm, and for 1300 nm $D=-140$ ps/(nm·km), $\sigma_\lambda=0,5$ nm. Furthermore, we use [8,9] for the calculation of the group delays, and values of differential mode attenuation (DMA) were computed according to [11], with respective parameters $\rho=9$, $\eta=7,35$, and intrinsic attenuation: 3

dB/km (850 nm), and 0,55 dB/km (1300 nm), respectively.

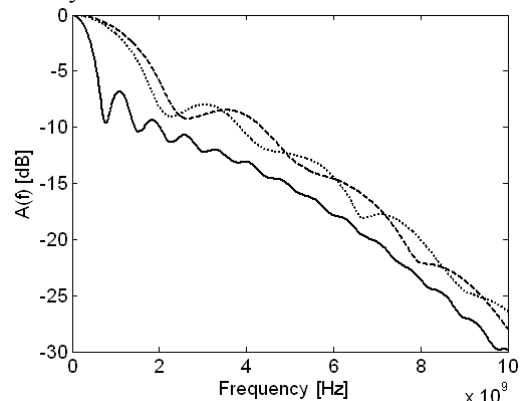


Figure 2. Mean frequency response for a fiber with a core diameter equal to 50 μm, L=1 km, NA=0.2, $\lambda=850$ nm, $D=-140$ ps/(nm·km), $\Delta\lambda=0.35$ nm, N=18, $g=2.15$. Mode launch according to (4). Solid lines – excited modes 1..18, dashed lines- excited modes 1..6, dotted lines- excited modes 7...12; $\sigma=0.5$

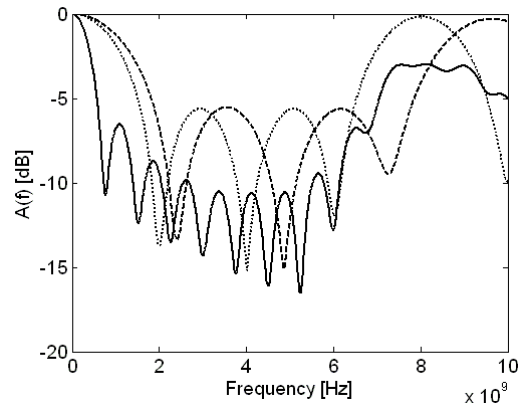


Figure 3. Mean frequency response for a fiber with a core diameter equal to 50 μm, L=1 km, NA=0.2, $\lambda=1300$ nm, $D=-10$ ps/(nm·km), $\Delta\lambda=0.5$ nm, N=11, $g=2.15$. Mode launch according to (4). Solid lines – excited modes 1..11, dashed lines- excited modes 1..4, dotted lines- excited modes 5...8; $\sigma=0.1$

A crucial factor influencing frequency response is the launch type expressed by mode group powers, P_k . Generally, there are uniform launches such as overfilled launch (OFL), where all modes have more or less equal powers, and restricted mode launches (RML), when only subsets of mode groups are excited and their powers are a function of k. In order to model the statistical variability of excitation a random factor was added to the expression for P_k . As a result, it was assumed in the calculus that the powers P_k are given by

$$P_k = \begin{cases} 1 + \alpha_k, & k_p \leq k \leq k_k \\ 0 & \end{cases} \quad (4)$$

for a uniform launch (excitation), and by

$$P_k = \exp \left[-\ln 2 \left(k - \frac{k_p + k_k}{2} \right)^2 / \left(\frac{k_k - k_p}{2} \right)^2 \right] (1 + \alpha_k) \quad (5)$$

for a restricted launch.

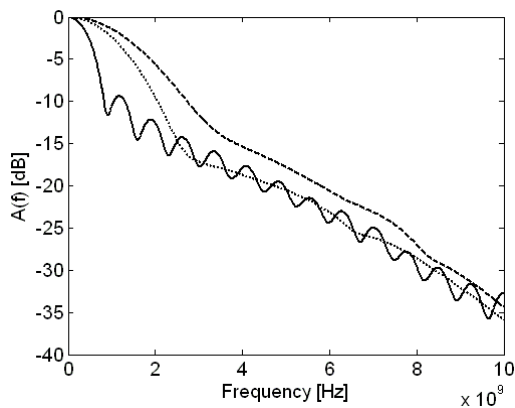


Figure 4. Mean frequency response for a fiber with a core diameter equal to 50 μm , $L=1$ km, $NA=0.2$, $\lambda=850$ nm, $D=-140$ ps/(nm·km), $\Delta\lambda=0.35$ nm, $N=18$, $g=2.15$. Mode launch according to (5). Solid lines – excited modes 1...18, dashed lines- excited modes 1...6, dotted lines- excited modes 7...12: $\sigma=0.1$

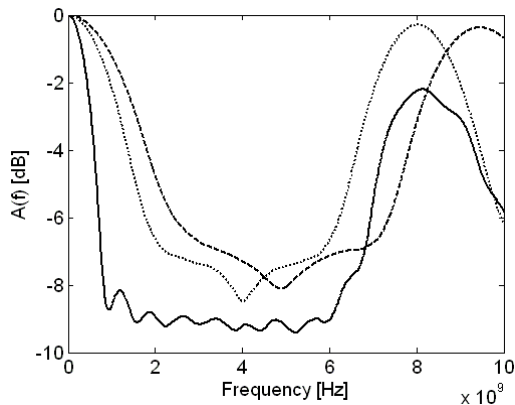


Figure 5. Mean frequency response for a fiber with a core diameter equal to 50 μm , $L=1$ km, $NA=0.2$, $\lambda=1300$ nm, $D=-10$ ps/(nm·km), $\Delta\lambda=0.5$ nm, $N=11$, $g=2.15$. Mode launch according to (5). Solid lines – excited modes 1...11, dashed lines- excited modes 1...4, dotted lines- excited modes 5...8: $\sigma=0.5$

In the formulas above, k_p and k_k determine the number of the first and the last excited mode groups (for a restricted launch those correspond to half maximum), σ is the standard deviation of the random factor, and x_k is the realization of a random variable with zero mean and unit variance. It turned out that the pdf of this variable has negligible impact on the results, therefore a uniform pdf was used throughout calculations. The form of eqn. (5) follows from the typical powers of mode groups obtained in restricted launches.

Due to a random factor used in calculation we define the mean frequency response as

$$A(f) = E \left\{ 10 \log_{10} \left| \frac{H(f)}{H(0)} \right| \right\} \quad [\text{dB}], \quad (6)$$

where E is the statistical mean operator. The values from eqns. (4), (5) as well as parameters for group delay, chromatic dispersion and DMA were inserted into (1) and

values of $H(f)$ for different realizations of random variables were calculated. Finally, the function $A(f)$ was obtained according to (6). The number of averaged functions $H(f)$ was sufficient to avoid any dependence on realization of random variables. The results are shown in Fig. 2...5 for the 10 GHz frequency range and two wavelengths 850 nm and 1300 nm. The profile parameter was set equal for the two wavelength ($g=2.15$) to obtain comparable baseband width.

In this study, we investigated the possibilities of signal transmission outside the baseband of MM fiber. It was proved that there are frequency passbands suitable for SCM transmission if the number of mode groups propagating is not too large and in the absence of mode mixing in the fiber. These conditions are usually satisfied for typical contemporary GI silica fibers. On the other hand, SI fibers are not suitable for SCM transmission due to a large number of modes propagating and strong mode group mixing. It was also shown that the widths of the passbands are directly related to the baseband width (they are usually equal). Given a GI silica fiber it is always better to use longer wavelengths, and a restricted mode launch (RML). The reason for this is that for short wavelengths chromatic dispersion plays an important role. Furthermore, as opposed to a short wavelength and an overfilled launch (OFL), a longer wavelength and RML result in fewer mode groups propagating in the fiber. Under these conditions the signal attenuation over the passbands is reduced. It is necessary to stress that these results have been obtained for regular profiles of refractive index. If this condition is not satisfied the mode group approach may not be suitable.

References

- [1] C. Xia, M. Ajgaonkar, W. Rosenkranz, *Journ. of Lightwave Techn.*, **23**, (2005) 2001
- [2] J. Siuzdak, G. Stepniak, L. Maksymiuk, *ECOC 2008, We.3.F.6*
- [3] N. Guan, K. Takenaga, S. Matsuo, and K. Himeno, *Journ. Lightwave Techn.*, **22**, (2004) 1714
- [4] A.M. Diab, J.D. Ingham, R.V. Penty, and I.H. White, *Journ. Lightwave Techn.*, **23**, (2005) 2380
- [5] E.J. Tyler, P. Kourtessis, M. Webster, E. Rochart, T. Quinlan, S.E. Dudley, S.D. Walker, R.V. Penty, and I.H. White, *Journ. Lightwave Techn.*, **21**, (2003) 3237
- [6] I. Gasulla, J. Capmany, *MWP'06*, (2006) 1
- [7] A. Diab, J.D. Ingham, R.V. Penty, I.H. White, *Journ. of Lightwave Techn.*, **23**, (2005) 2380
- [8] H. Unger, *Planar optical waveguides and fibres*, Oxford University Press, Oxford 1977
- [9] R. Olshansky, D.B. Keck, *Applied Optics*, **15**, (1976) 483
- [10] J. Siuzdak, R. Nowak, G. Stepniak, *Proceedings of the ISCA Conference*, 2005
- [11] G. Yabre, *Journ. of Lightwave Techn.*, **18**, (2000), 166-177, February 2000