Adam NIKOŁAJEW
Bialystok University of Technology, Faculty of Electrical Engineering

Bandwidth of multimode step-index optical fibre in dependence on its parameters

***Abstract**. Bandwidth of step index optical fiber is analyzed basing on its impulse response, calculated in dependence on diameter of the core, length of the fiber and refractive profile. Maxwell's equations were used to obtain fiber's impulse response. Bandwidth of step index multimode optical fiber depends strongly on its length and numerical aperture.*

***Streszczenie.** Przeprowadzono analizę pasma wielomodowego światłowodu skokowego na podstawie jego odpowiedzi impulsowej, obliczonej na podstawie równań Maxwella w zależności od średnicy rdzenia, długości i profilu refrakcyjnego światłowodu. Stwierdzono, że pasmo światłowodu zależy gównie od długości włókna i jego apertury numerycznej (**Pasmo wielodomowego światłowodu skokowego w zależności od jego parametrów**).*

Keywords: step-index optical fibre, bandwidth, impulse response
Słowa kluczowe: światłowód skokowy, pasmo, odpowiedź impulsowa

Introduction

Modal dispersion is the basic mechanism of deformation of output signal of multimode optical fiber. Radiant energy is transmitted along the core in form of modes, moving with various velocities. It causes that particular fragments of signal's energy reach the end of fiber at different times. It delimits as well signal's bandwidth and distance of transmission.

Bandwidth of step index multimode fiber as a function of its length is calculated using approximate methods [1, 2, 3], but influence of the other fiber's parameters on the quality of transmission has not been considered.

Investigations of effect of multimode fiber's parameters on its bandwidth is the purpose of this article. Considered fiber is excited by monochromatic radiation of wavelength λ = 1,55 µm. Waveguide and chromatic dispersions also attenuation of the signal are ignored.

Impulse response of the fiber

The number of modes, propagating along multimode step index fiber with different propagation constants is a function of normalized frequency V, given by the formula [1]

$$V = \frac{2 \cdot \pi \cdot a}{\lambda} \cdot NA \,, \tag{1}$$

$$NA = \sqrt{n_1^2 - n_2^2} \,, \tag{2}$$

where a is a radius of fiber's core, NA – numerical aperture, n_1 and n_2 are refractive indexes of fiber's core and cladding, respectively. Transverse components u of propagation constants of particular modes can be obtained as solutions of set of equations [4]:

(3)
$$\left[\frac{J'_m(ua)}{uaJ_m(ua)} + \left(\frac{n_2}{n_1}\right)^2 \frac{K'_m(wa)}{waK_m(wa)}\right]\left[\frac{J'_m(ua)}{uaJ_m(ua)} + \frac{K'_m(wa)}{waK_m(wa)}\right] = \left[\frac{1}{(ua)^2} + \frac{1}{(wa)^2}\right]\left[\frac{1}{(ua)^2} + \left(\frac{n_2}{n_1}\right)^2 \frac{1}{(wa)^2}\right]$$

$$u^2 + w^2 = k_0^2 \cdot \left(n_1^2 - n_2^2\right). \tag{4}$$

w denotes transverse component of mode's propagation vector inside the fibre cladding, k_0 – wavenumber of electromagnetic wave of wavelength λ in free space. J_m is the mth order Bessel's function of the first kind, K_m – the mth order modified Bessel's function of the second kind. m denotes an integer number equal 0 for TM and TE modes, 1,2,3,… for HE and -1,-2,-3,… for EH modes.

Every mode of transverse component of propagation constant u reaches the end of fiber of length L after time t.

$$t = \frac{n_1 \cdot L}{c} \cdot \frac{n_1 \cdot k_0}{\sqrt{n_1^2 \cdot k_0^2 - u^2}} \tag{7}$$

where c is velocity of light in free space .

Solutions of set of equations (3) – (4) and approximation of steady state modal power distribution [5,6] enable calculations of fiber's impulse response.

Impulse response of the fiber was calculated as the sum of optical power, reaching the end of the fiber at specified moments [7-9]. All propagating mode reach the end of fiber during the time interval

$$\Delta t = \frac{n_1 \cdot L}{c} \cdot \left(\frac{n_1}{n_2} - 1\right). \tag{8}$$

Sampling time was estimated as Δt / 30. Exemplary impulse responses of the fiber, calculated for a = 200 µm, n_1 = 1,48, n_2 = 1,46 and L = 100 m, L = 300 m, L = 600 m and L = 900 m are shown on Fig. 1.

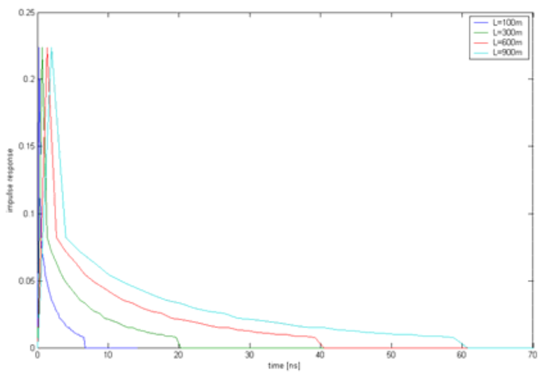

Fig. 1. Impulse response of optical fiber dependence on its length

It is visible, that impulse responses for different lengths of fibers have similar shape, but their duration increases proportionally to length of the fiber.

Amplitude characteristics and bandwidth of the fiber

Impulse response of the fiber enables calculation of its amplitude characteristics. Because impulse response is discrete, Fast Fourier's Transform (FFT) should be used. To calculate 64-point FFT impulse response must have 64 elements, so it has been filled with zeros. Amplitude characteristics is a modulus of FFT. Every characteristics has been normalized, so as its maximum equals 1. Basing on these characteristics, approximations of 3 dB bandwidth is possible.

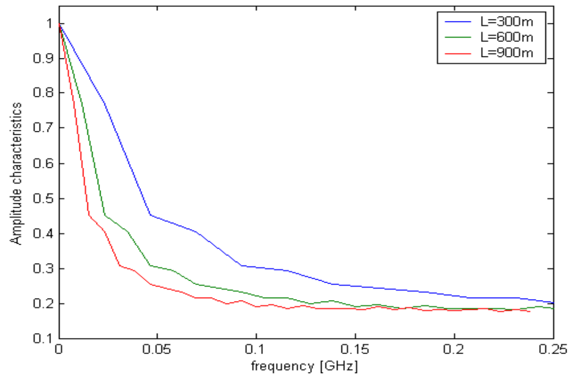

Fig. 2. Amplitude characteristics of fibers of lengths L= 300 m L = 600 m and L = 900 m

Bandwidth of the fiber as a function of its parameters

Calculations of fiber's bandwidth were performed in dependence on its length, diameter of its core, and refractive indexes in core and cladding areas. Results of simulations are shown on Figures 3 – 5.

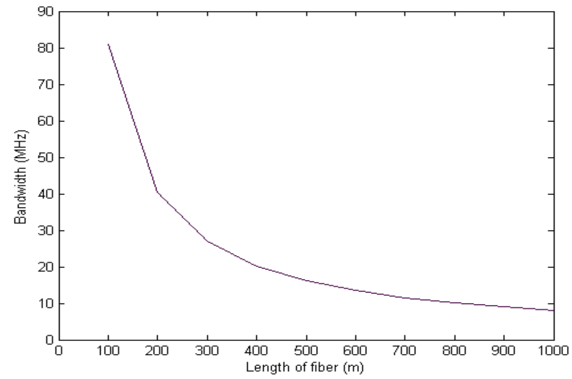

Fig 3. Bandwidth of the fiber in dependence on its length, a = 0.2 mm

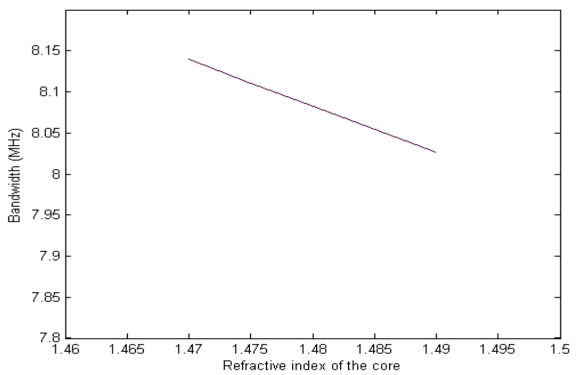

Fig 4. Bandwidth of the fiber in dependence on refractive index of the core, a = 0.2 mm, L =1000 m, NA = 0,25

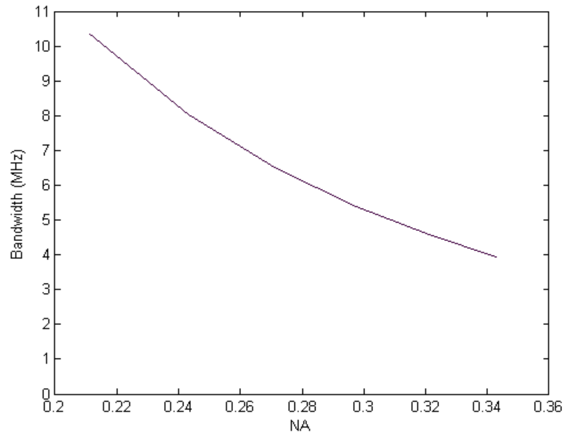

Fig 5. Bandwidth of the fiber in dependence on NA, a = 0.2 mm, L =1000 m, n_1 = 1,49

Effect of diameter of the fiber's core on bandwidth is unimportant.

Conclusions

Results of calculations show, that the most significant effect on bandwidth of step index multimode optical fiber have two parameters: length of the fiber and its numerical aperture. Impulse response of longer fiber spreads out over a time. Fiber's bandwidth decreases proportionally to increase of its length. Greater value of fiber's numerical aperture increases range of propagation constants of propagated modes. It lengthens impulse response of the fiber and delimits its bandwidth. Effect of the other considered parameters of the fiber is unimportant and can be ignored.

REFERENCES

[1] Ishigure T., Kano M., Koike Y.: Which is a more serious factor to the bandwidth of GI POF – differential mode attenuation or mode coupling. *J. Lightwave Technol.* 18, 959 - 965, (2000).
[2] Mateo J., Losada M.A., Zubia J.: Frequency response in step index plastic optical fibers obtained from generalized power flow equation. *Opt. Express* 17,2850 -2860, (2009)
[3] Savovic S., Djordjevich A. : Influence of numerical aperture on mode coupling in step index plastic optical fibers. *Appl. Opt. 43,* 5542 - 5546 (2004).
[4] Okamoto K.: Fundamentals of optical waveguides. Elsevier, (2006)
[5] Nikołajew A.: Method of determination modal power distribution in step-index optical fibre. *Przeglad Elektrotechniczny,* 8/2008, 164 -166.
[6] Nikołajew A.: Method of forming step-index optical fibre's luminous intensity. *Przeglad Elektrotechniczny,* 8/2008, 161 – 163
[7] Nikołajew A.: Regeneration of step-index optical signal using FIR filters. *Przeglad Elektrotechniczny,* 3/2010, 67 – 68
[8] Nikołajew A.: Application of quadrature mirror filters to receipt of step-index optical fibre's output signal. *Przeglad Elektrotechniczny,* 3/2010, 65 – 66
[9] Nikołajew A.: The colour of the light emitted by step-index fiber. *Przeglad Elektrotechniczny,* 5/2007, 47 – 49

Author*: dr inż. Adam Nikołajew, Politechnika Białostocka, Wydział Elektryczny, ul. Wiejska 45 D, 15-965 Białystok, e-mail: adamnikolajew@pb.edu.pl*