Adam NIKOŁAJEW

Bialystok University of Technology, Faculty of Electrical Engineering

Effect of dispersion on bandwidth of single mode optical fiber

***Abstract**. Dependence of spectrum of transmitted signal and parameters of single mode optical fiber on its bandwidth is analyzed. Wide spectrum of signal reduces bandwidth in a large degree. Length of fiber also significantly reduces bandwidth of single mode fiber.*

***Streszczenie.** Przeprowadzono analizę zależności pasma światłowodu jednomodowego w zależności od jego parametrów i widma sygnału. Szerokie widmo sygnału oraz długość włókna znacznie redukują pasmo światłowodu (**Wpływ dyspersji na pasmo światłowodu jednodomowego**).*

Keywords: single mode, optical fibre, bandwidth, spectrum
Słowa kluczowe: światłowód jednomodowy, pasmo, widmo

Introduction

Chromatic and waveguide dispersions are basic mechanisms of deformations of signal, transmitted along single mode optical fiber.

Most of publications [1-4,6], considering single mode optical fibers present delay of the signal, but they do not consider effect of spectrum of guided light on fiber's bandwidth.

Calculations basing on Maxwell's equations enable considerations of bandwidth of the fiber in dependence on its parameters as well as spectrum of guided radiation.

Propagation of the light inside step index single mode optical fiber

The number of modes, propagating along step index optical fiber is determined by its normalized frequency V.

(1) $$V = \frac{2\cdot\pi\cdot a}{\lambda}\cdot\sqrt{n_1^2 - n_2^2}$$

a denotes a radius of the core, λ – wavelength of guided light, n_1 and n_2 are refractive indexes of the core and cladding. Optical fiber guides only single mode on condition, that its normalized frequency is less than first zero of first order Bessel's function of the first kind $J_1(x)$, i.e. V < 2.405 [1]. It delimits both diameter of the core and numerical aperture of the fiber.

Single-mode optical fiber of core's diameter $2\cdot a$ = 9 μm is considered. Attenuation of a signal is ignored. Taking into account, that laser diode is usually a source of signal, Gaussian spectrum of light is assumed. Calculations are performed for different FWHM of spectrum, described by following formula [6]

(3) $$P(\lambda) = \exp\left[-2\cdot\ln^2 4\cdot\frac{(\lambda-\lambda_0)^2}{FWHM^2}\right].$$

The third transmission window is considered, therefore λ_0 = 1,55 μm was chosen. Chromatic dispersion of cladding is described by the formula [5,6],

(4)
$$n_2(\lambda) = C_0 + C_1\lambda^2 + C_2\lambda^4 + \frac{C_3}{(\lambda-\lambda_1)} + \frac{C_4}{(\lambda-\lambda_1)^2} + \frac{C_5}{(\lambda-\lambda_1)^3}$$

where: C_0 =1.4508554, C_1 = -0.0031268, C_2 = -0.0000381, C_3 = 0.0030270, C_4 = -0,0000779, C_5 = 0.0000018, λ_1 = 0.035 nm. Refractive index of the core can be obtained as

(5) $$n_1(\lambda) = n_2(\lambda) + \Delta n\ .$$

Numerical aperture of the fiber as well as FWHM of spectrum must be chosen in order that normalized frequency V < 2,405.

To obtain delay of radiation of wavelength λ, running along the fiber of length L, transverse components u and w of propagation constants inside the core and the cladding should be calculated. For single-mode optical fiber set of following equations must be solved [1-4]:

(6)
$$\left[\frac{J_1'(ua)}{uaJ_1(ua)} + \left(\frac{n_2}{n_1}\right)^2\frac{K_1'(wa)}{waK_1(wa)}\right]\left[\frac{J_1'(ua)}{uaJ_1(ua)} + \frac{K_1'(wa)}{waK_1(wa)}\right] = \\ = \left[\frac{1}{(ua)^2} + \frac{1}{(wa)^2}\right]\left[\frac{1}{(ua)^2} + \left(\frac{n_2}{n_1}\right)^2\frac{1}{(wa)^2}\right]$$

(7) $$(ua)^2 + (wa)^2 = V^2\ .$$

where K_1 is the first order modified Bessel's function of the second kind.

Light of propagation constant u reaches the end of fiber of length L after time

(8) $$t = \frac{n_1\cdot L}{c}\cdot\frac{k_1}{\sqrt{k_1^2 - u^2}}\ ,$$

where c is velocity of light in free space and k_1 – propagation constant inside fiber's core. Dependence of time t on wavelength λ is shown on Fig. 1. Calculations were performed for L=1000 m and Δn = 0,005.

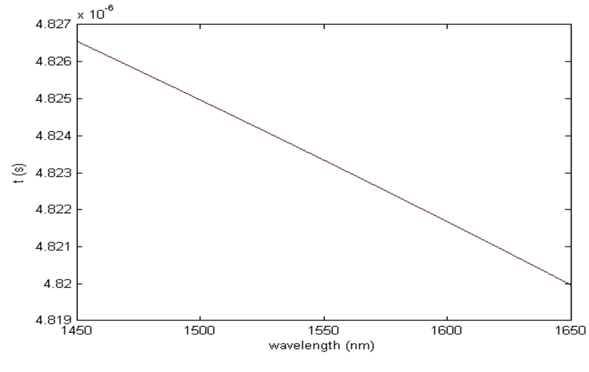

Fig. 1. Time t as function of wavelength, L = 1000 m and Δn = 0,005

Impulse response and bandwidth of the fiber

Impulse response of the fiber is calculated as the sum of power, reaching the end of the fiber [7-11]. Calculations are performed for FWHM = 1 – 10 nm and input signal in form of Dirac's impulse. Rise time of signal is not taken into considerations.

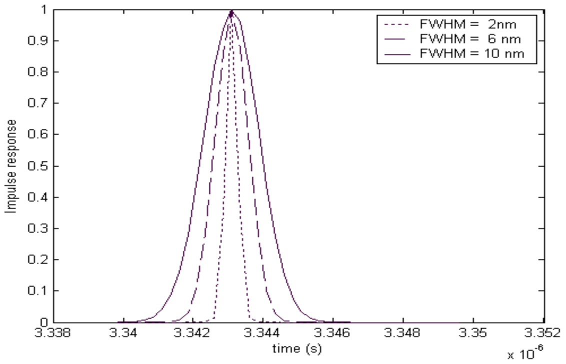

Fig. 2. Impulse response of the fiber for L=1000 m and Δn = 0,005

Transforming impulse response of the fiber using Fourier's transform, amplitude characteristics and 3 dB bandwidth of the fiber can be obtained (Fig. 3).

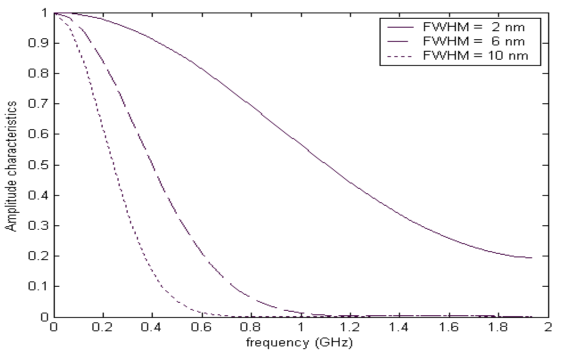

Fig. 3. Amplitude characteristics for L =1000 m and Δn = 0,005

Dependence of fiber's bandwidth on its parameters and spectrum of signal

Method of calculations enables determination of 3 dB bandwidth in dependence on different parameters of the fiber and spectrum of transmitted signal. Figure 4 presents dependence of bandwidth on spectrum of the signal. Calculations were performed for L = 1000 m and Δn = 0,005.

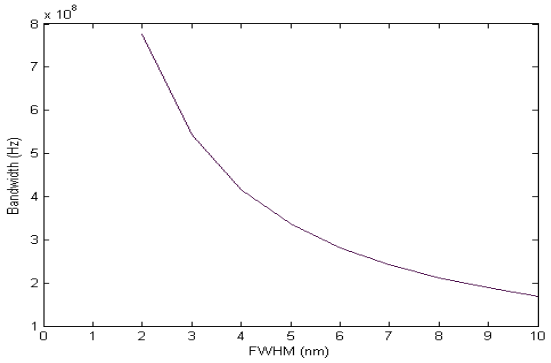

Fig. 4. Bandwidth of the fiber in dependence on FWHM of the signal for Δn = 0,005 and L = 1000 m

Analyzing influence of parameters of the fiber on its bandwidth, its length L and difference of refractive indexes Δn have been taken into consideration. Effect of length on the fiber's bandwidth is presented on Fig. 5.

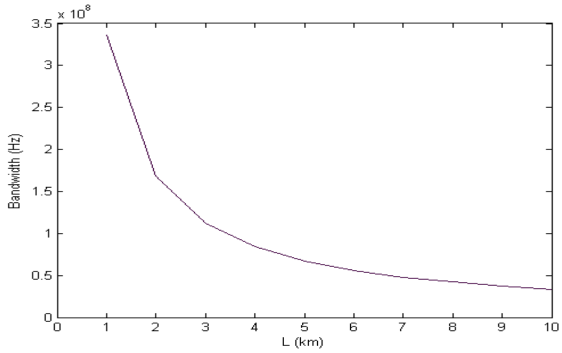

Fig. 5. Bandwidth of the fiber in dependence on its length L for Δn = 0,005 and FWHM = 5 nm

Change of Δn modifies solution of Hondros-Debye's equation, therefore effect of Δn on fiber's bandwidth is considered. However influence of refractive profile on fiber's bandwidth is considerably less than effect of length and spectrum.

Conclusions

Results of calculations show, that reduction of single mode optical fiber's bandwidth is caused by two fundamental reasons: chromatic dispersion and elongation of fiber. As it is visible on Fig. 3, widening of spectrum makes impulse more stretched in time domain, what reduces data transfer speed. This effect can be reduced, if solutions of Hondros-Debye's equation are independent on wavelength. To realize it, two conditions must be satisfied: normalized frequency of the fiber cannot be dependent on wavelength and ratio n_1/n_2 = const. Both conditions are satisfied when refractive indexes of the core and cladding are proportional to wavelength.

Reduction of fiber's bandwidth, caused by its length is evident and it does not require more comments. Results of calculations reveal, that difference of refractive indexes changes bandwidth of the fiber in small degree.

REFERENCES

[1] Siuzdak J.: Wstęp do współczesnej telekomunikacji światłowodowej, WKiŁ, Warszawa 1997
[2] Okamoto K.: Fundamentals of optical waveguides. Elsevier, (2006)
[3] Midwinter K. E.: Światłowody telekomunikacyjne. WNT, Warszawa 1983
[4] Einarsson G.: Podstawy telekomunikacji światłowodowej. WKŁ, Warszawa 1996
[5] Peak U.C., Peterson G. E., Carnevale A.: Dispersion single mode light guides with α-index profiles. *Bell Syst. Tech. J.*, 60, 583 (1981)
[6] Ziętek B. : Optoelektronika. Wyd UMK, Toruń 2004.
[7] Nikołajew A.: Method of determination modal power distribution in step-index optical fibre. *Przeglad Elektrotechniczny,* 8/2008, 164 -166.
[8] Nikołajew A.: Method of forming step-index optical fibre's luminous intensity. *Przeglad Elektrotechniczny,* 8/2008, 161 – 163
[9] Nikołajew A.: Regeneration of step-index optical signal using FIR filters. *Przeglad Elektrotechniczny,* 3/2010, 67 – 68
[10] Nikołajew A.: Application of quadrature mirror filters to receipt of step-index optical fibre's output signal. *Przeglad Elektrotechniczny,* 3/2010, 65 – 66
[11] 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*