ACOUSTIC WAVE PROPAGATION IN OPTICAL FIBER

Milan Holík

Doctoral Degree Programme (1), FEEC BUT

E-mail: xholik02@stud.feec.vutbr.cz

Supervised by: František Urban

E-mail: urban@feec.vutbr.cz

Abstract: The acoustic wave propagation theory the optical fibers are summarized in this article. The numeric model of acoustic wave propagation in optical fiber has been programmed in Matlab. This model we used for new optical sensors application. The main behavior of acoustic wave goes through fiber is the change of refractive index. Dependence between % change of wave amplitude and distance from source of pulse is most significant for the wide field of the sensors applications. The acoustic wave main features acquired from simulation in Matlab.

Keywords: refractive index, acoustic wave, optical sensor, Matlab

1. INTRODUCTION

Standard acoustic wave propagate through air bythe change of its density. The same acoustic wave propagates through optical fiber by the change of density of a glass - change of refractive index. The standard optical fiber has refractive index 1.458. Comparison of significant parameters of the air and glass are in the Table 1. Acoustic wave propagation in gas and solid material is quite different. There are differences of basic material constants for example density, viscosity and else.

	n	vc	ε_r	ρ	E
	(-)	(m/s)	(-)	(kg/m3)	GPa
Air	1	343	1	1,21	x
Glass SiO2	1,458	5200	3,75	2200	72

Table 1: Compare Air and Glass

There are some possibilities to make acoustic wave in the fibers. One of these is based on stimulated Brillouin scattering (SBS). This principle can be used at any wavelength where the fiber is transparent. (Zhu, 2007) Other principles are based on mechanical stress of the fiber. These methods have the same working range like as method based on the SBS. The main advantage of the mechanical methods is really higher amplitude of acoustic wave in the fiber. The experiment made by Zhaoming Zhu, Daniel J. Gauthier and Robert W. Boyd shows the method of the storage light pulses in fiber by SBS.We used theirs measured parameters to control output of our presented simulation.

Acoustic wave traveled distance approx. 62.4um for 12ps. This light pulse lost 70% of its amplitude. (Zhu, 2007) The relationship between acoustic wave amplitude and its frequency is the main output of our simulation. Next important output is the shape of the acoustic wave. We start with programing simulation for these outputs in the Matlab software. The simulation is based on the mathematical model of acoustic wave.

2. MATEMATICAL MODEL OF ACOUSTIC WAVE

The outputs of the mathematical model depend on the shape on the stress pulse of this acoustic wave. First, the mechanical pulses are sort to discontinuous and continuous (Brepta, Okrouhlík, & Valeš, 1985). These two basic pulses have different stress pulse and its spectrumis in Fig. 1.

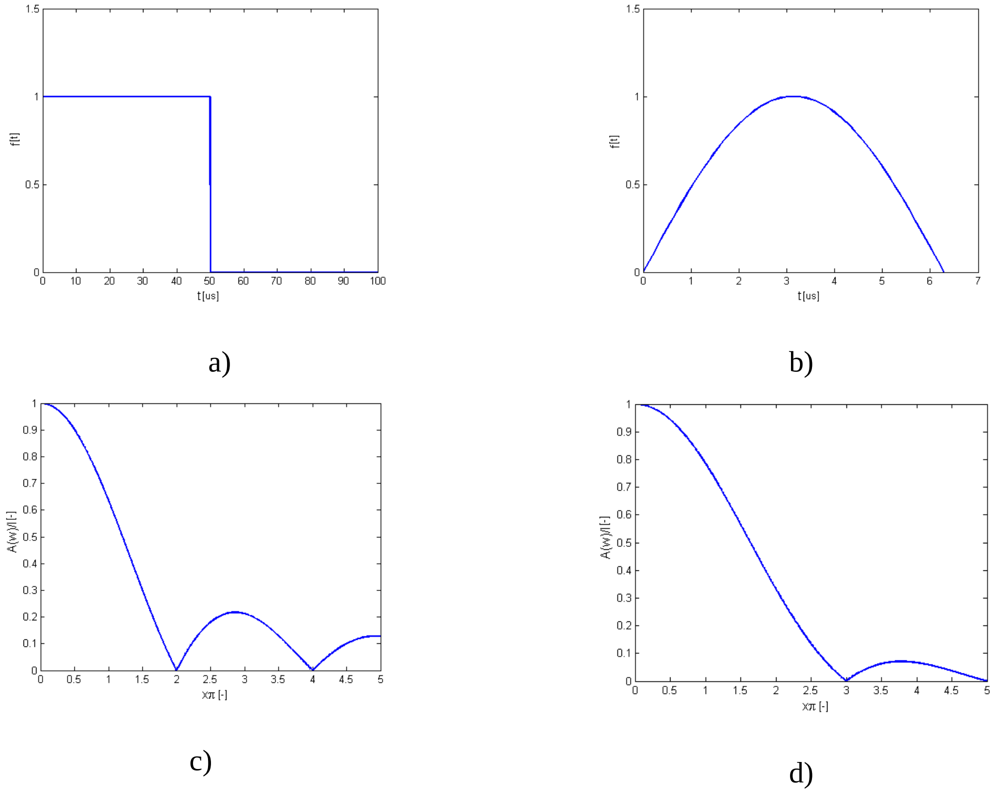


Figure 1 Types of stress pulses

a) Discontinuous stress pulse c) Discontinuous stress spectrum

b) Continuous stress pulse d) Continuous stress spectrum

The spectrum of discontinuous and continuous stress gives by Eq. 1 for discontinuous steress and Eq. 2 for continuous stress.

$$\frac{A(\omega)}{I} = 2 \cdot \left| \frac{\sin\left(\frac{x\pi}{2}\right)}{x\pi} \right| \tag{1}$$

$$\frac{A(\omega)}{I} = \left| \frac{\cos\left(\frac{x\pi}{2}\right)}{1-\left(\frac{x\pi}{\pi}\right)^2} \right| \tag{2}$$

The basic simple elastic lattice is in Fig 2. This model consist point particles and linear springs. The point particles are a solid and the linear springs are an immaterial. The longitudinal displacements caused by longitudinal wave are given by Eq. 3.

$$u_k = U_0 e^{i(\gamma k - \omega t)} \tag{3}$$

Where U_0 is wave amplitude, $\gamma = 2\pi/\Lambda$ is real wave number and. Λ is wave period.

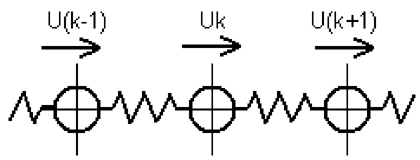


Figure 2 Simple lattice

Wave number can be a complex variable. Wave phase speed is given by Eq. 4.

$$vc = \frac{\omega}{\varphi} = \lambda f \tag{4}$$

Where $\omega = 2\pi f$ and $\varphi = 2\pi/\lambda$.

Dumping effect can be simply modeled by method of the Kelvin-Voigt element (KVM). It use parallel viscosity element. Mode is shown in Fig. 3.

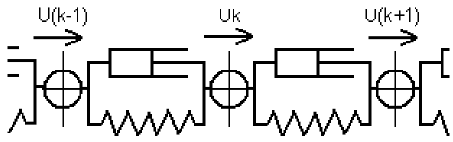
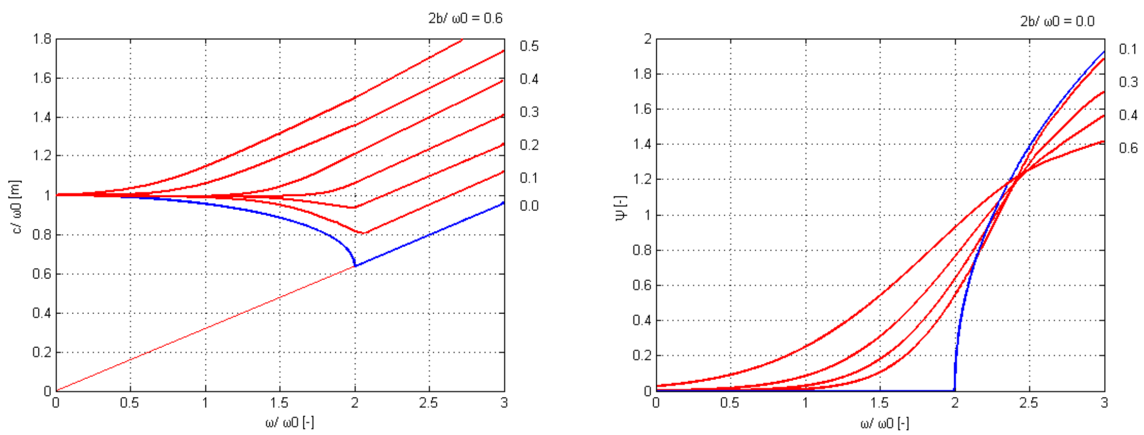


Figure 3 Lattice formed by Kelvin-Voigt elements

Phase speed defined by the KVM method is given by Eq. 5. Dumping factor is given by Eq. 6. We used these equations to the model of the KVM method with zero viscosity, see the blue curves in Fig.4 a, b. Only these curves for zero viscosity we simulated by our programmed model by Eq. 5 and Eq. 6. A red curves from Fig. 4 corresponds with dumping effect. These curves we implement only for illustration of model behavior, dumping factor is equal to $2b/\omega_0$.

$$\frac{c}{\omega_0} = \frac{\frac{\omega}{\omega_0}}{arccos\left(\frac{2-\omega^2/\omega_0^2}{2}\right)} \tag{5}$$

$$\psi = \arg cosh\left[\frac{1}{2}\left(\frac{\omega}{\omega_0}\right)^2 - 1\right] \tag{6}$$



a) b)

Figure 4 Behavior of KVM

a) Dispersive diagram for a simple lattice formed by Kelvin-Voigt elements

b) Damping factor for a simple lattice formed by Kelvin-Voigt elements

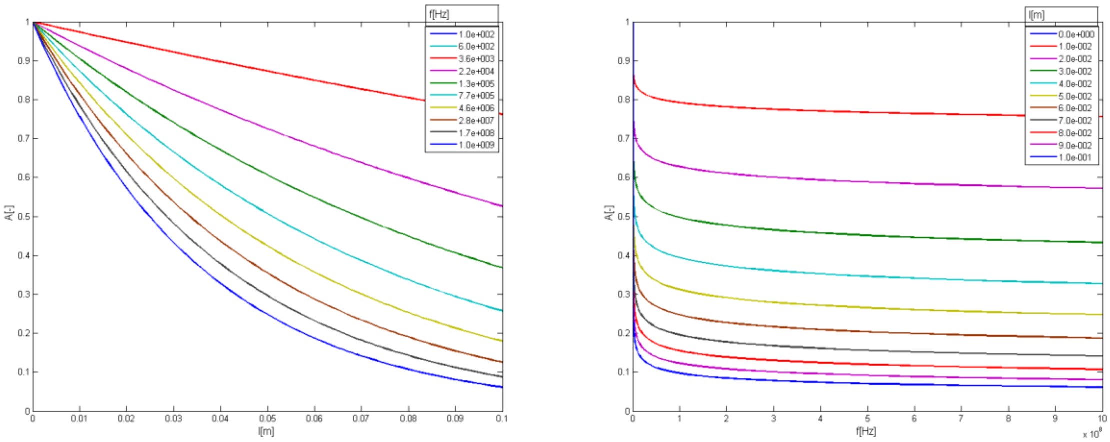
The blue curves we need for our applications. Simple lattice transports longitudinal harmonic waves with band from 0 to $2\omega_0$ with zero attenuation for zero dumping factor is in the Fig. 4 b). The dispersion of the lattice in the same band from 0 to $2\omega_0$ is in the Fig. 4 a). The attenuation of the lattice is increasing with the frequency band over $2\omega_0$. On the other side the amplitude is exponentially decreasing in the frequency band over $2\omega_0$. This is valid for infinite lattice.

3. MODEL DESCRIPTION

We used non – dispersion medium, zero viscosity and the model was programmed for frequency band over 2 ω_0. These conditions are our primary conditions to realization model. The non-dispersion medium means the phase speed is the same for whole frequency band.We can expect zero viscosity due to viscosity of the glass is small. The viscosity of the glass is 0.001 (Univezita Tomáše Bati ve Zlíně, 2009). This is neglect KVM dumping factor. Next we used the envelope of harmonic wave. It is given by Eq. 7.

$$A = \exp(-\psi l) \quad (7)$$

Attenuation coefficient of wave vs. distance describes influence of band over ω_0, see Fig. 5 a). First two frequencies have zero attenuation. Dependence of the attenuation coefficient of wave on the frequency is shown in Fig. 5 b). Zero attenuation of low frequency band with distance as parameter can be seen in this figure. The complex image of results is shown in Fig.6 by 3D graph.



a) b)

Figure 5 Behavior of model

a) Attenuation coefficient of wave vs. distance and frquency as parameter

b) Attenuation coefficient of wave vs. frequency and distace as parameter

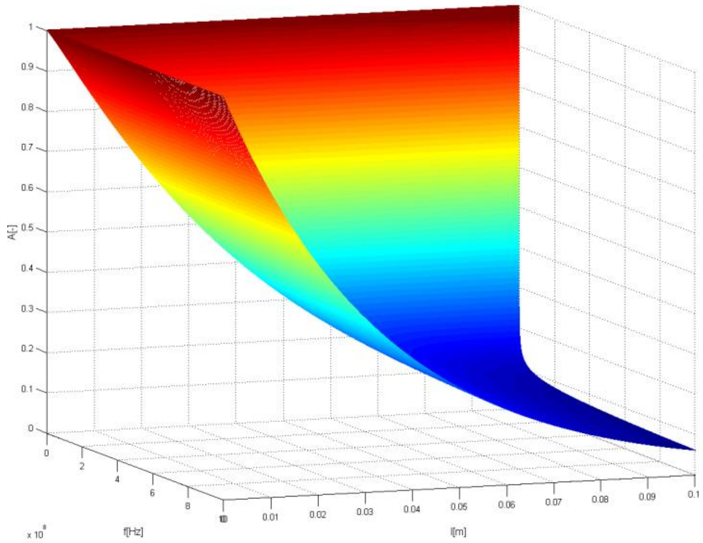


Figure 6 3D graph of acoustic wave attenuation coefficient in thin rod

4. CONCLUSION

We prepared model to simulation of the propagation of the acoustic wave in the solid. We presented first results of our first simplified models. Our results promise new possibilities of using of the model of the propagation of theacoustic waves in the field of optical fibers. We verify the amplitude is exponentially decreasing in the frequency band over $2\omega_0$. We expect development of the model to observe dependence of the refractive index on the amplitude and on the frequency of the acoustic wave.

ACKNOWLEDGEMENT

The authors wish to express thanks for support to grant project from Technology Agency of the Czech Republic, project NO. TA01030859.

REFERENCES

[1] Brepta, Rudolf, Okrouhlík, Miloslav and Valeš, František. *Vlnové a rázové děje v pevných tělesech a metody jejich řešení.* Praha : Academia, 1985. 21-067-85.

[2] Univezita Tomáše Bati ve Zlíně. Environmentální fyzika. *Ústav fyziky a materiálového inženýrství.* [Online] 2009. [Cited: 02 20, 2012.] http://ufmi.ft.utb.cz/texty/env_fyzika/EF_06.pdf.

[3] Zhu, Daniel J. Gauthier and Robert W. Boyd. Stored Light in an Optical Fiber via Stimulated Brillouin Scattering. *Science.* 5857 , 2007, Vol. Vol. 318, 1748-1750 .