Optical and Acoustical Methods in Science and Technology

Non-Contact Interaction of Ultrasonic Wave on Laser Beam

S. Muc*, T. Gudra and E. Bereś-Pawlik
Institute of Telecommunications, Teleinformatics and Acoustics, Wrocław University of Technology
Wybrzeże Wyspiańskiego 27, 50-370 Wrocław, Poland

The article presents the results of Matlab simulations and experimental studies of non-contact influence of ultrasonic wave on laser beam. A role of the air-gap and the influence of the air-gap on laser-ultrasonic transmission in optical fiber were examined. Two optical fibers were used with air-gap between them. One fiber was attached to a laser diode and positioned to pass through a hole in a sandwich type transducer and in a velocity transformer. In the velocity transformer (at its end), after leaving small air-gap, to the end of the transformer, the other optical fiber is attached. The second fiber can interact with a given biological structure.

PACS: 43.35.Yb, 42.81.Wg

1. Introduction

There are some possibilities of using laser radiation and low frequency, high intensity ultrasounds simultaneously: introducing ultrasound oscillations in the optical fiber by the stiff fixing it to a vibrating element [1–5] and non-contact influence of the ultrasonic wave on the laser beam. Literature [6–10] provides descriptions of the use of non-contact interaction. However, details concerning the role of the air-gap and the way both types of energy interact are scarce. The role of the air-gap, and its influence on laser-ultrasonic transmission in optical fiber was examined. Two optical fibers were used with air-gap between them. One fiber was attached to a laser diode and positioned to pass through a hole in a sandwich type transducer and a velocity transformer. In the velocity transformer (at its end), after leaving small air-gap, the other optical fiber is attached. The second fiber can interact with a given biological structure. The following study results are to help to provide information on whether ultrasounds can affect the parameters of light wave propagating in an optical fiber and through an air-gap.

2. Theoretical analysis

Literature provides examples of optical fiber sensors (FOS) that utilize an air-gap. These include extrinsic Fabry–Perot interferometer sensors (EFPI) [11–15]. In such sensors the second fiber is a reflecting one. There are also descriptions of a transmission-type Fabry–Perot sensor [16–20]. The non-contact interaction of ultrasonic wave on optical wave is analogous to the way a transmission-type Fabry–Perot sensor works. In this case the second optical fiber is not a reflecting one but light enters it. Figure 1 shows a measurement system for non-contact interaction of ultrasonic wave on optical wave.

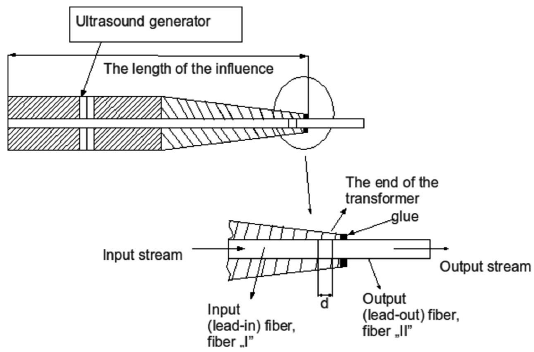

Fig. 1. A block diagram of a measurement system for non-contact interaction of ultrasonic wave on optical wave (d — the length of the air-gap).

Since a fraction of light is reflected from the surface of fiber "II", there are two propagation paths of optical wave in this waveguide [19].

The use of an air-gap allows interaction of three phenomena: phase modulation caused by altering refraction index, amplitude modulation in the air-gap caused by altering gap length and vibration of the tip of fiber "II". Additionally, amplitude loss of the propagating signal occurs. These are a result of signal scattering in the air-gap. The loss depends on the length of the air-gap.

Theoretically 3 examples of setups for non-contact interaction of ultrasonic wave on optical wave that use an air-gap can be considered: fiber "I" and fiber "II" are single-mode (Fig. 2a), fiber "I", and fiber "II" are multimode (Fig. 2c), fiber "I" is single-mode and fiber "II" is multimode (Fig. 2b).

After light passes through the gap it is not only attenuated but also scattered. As a result the example with two single-mode optical waveguides is very difficult to realise. Since the second fiber can interact with the biological structure, the combined laser-ultrasonic interaction that involves the use of an air-gap can be applied in surgery for biological structure cutting. In this case,

* corresponding author; e-mail: Sylwia.Muc@pwr.wroc.pl

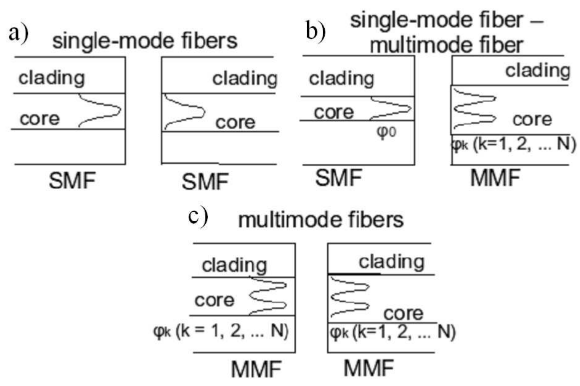

Fig. 2. Methods of non-contact interaction of ultrasonic wave on optical wave, using an air-gap, (a) two single-mode optical fibers, (b) one single-mode fiber and another multimode one, (c) two multimode fibers.

due to the thickness of the fiber used in surgery, only multimode optical fibers seem suitable, although the second fiber should have a core of larger diameter in order to facilitate easy input of optical wave.

3. Numerical simulations

A number of simulations in Matlab environment have been performed in order to check in what way the length of the air-gap affects optical wave (Fig. 3). For air-gap

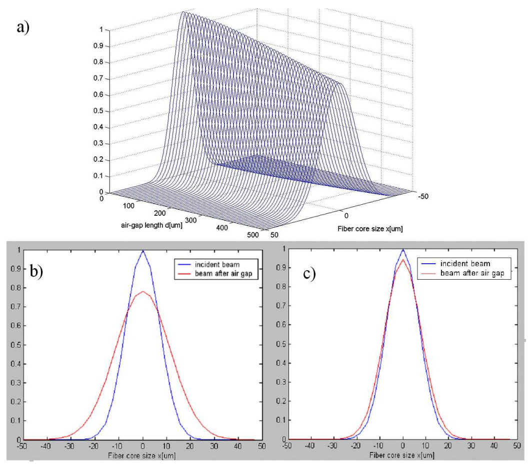

Fig. 3. The results of Matlab simulation of the relation of the effect the air gap has on optical wave: (a) 3D graph, (b) 2D graph, air-gap = 500 μm, (c) air-gap = 200 μm.

length of 200 μm amplitude loss is minor (see Fig. 3c). At gap length of 500 μm amplitude drops by about 20% and there is significant scattering of optical signal (Fig. 3b).

4. Experimental study

The research team performed experimental study concerning the effect the length of the air-gap has on ultrasonic wave propagating in a optical waveguide. The dependence of the amplitude of the ultrasonic output signal on the air-gap between two fibers is presented in Fig. 4.

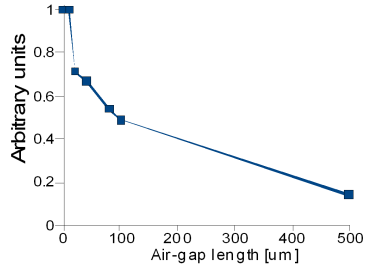

Fig. 4. The dependence of the amplitude of ultrasonic output signal on the length of the air-gap.

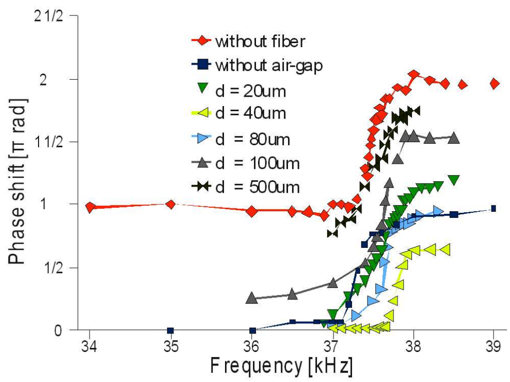

Fig. 5. Phase shift relation between input and output ultrasonic signal.

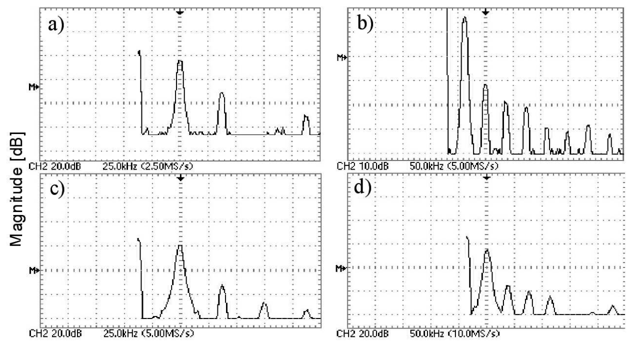

Fig. 6. Ultrasonic output signal spectrum: (a) from a sandwich transducer, (b) after attaching an optical fiber without an air-gap, (c) after attaching an optical fiber with an air-gap = 10 μm, (d) after attaching an optical fiber with an air-gap = 100 μm. Fiber length l = 15 cm.

With the increase of the air-gap the amplitude of the ultrasonic signal output decreases — it is exponential dependence. The decrease of the amplitude of ultrasonic signal in the air-gap is caused by strong attenuation of ultrasonic wave propagating in air environment.

For the transducer without an optical fiber it changes in the range of 1 to 2π rad. Attaching an optical fiber to the transducer causes change in the phase shift between input and output ultrasonic signal. In case of the studied optical fibers, phase shifts are adjacent to one another and change from 0 to π rad [4] (see Fig. 5). When using an air-gap, its low length results in phase shift behaving similarly to the case in which the optical fiber is glued with no air-gap. Air-gap over 100 μm means that phase shift is closer and closer to the values standard for a setup without a glued optical waveguide. The phase shift relation between input and output ultrasonic signal is shown in Fig. 5.

Attaching a fiber produces harmonics in output ultrasonic signal. When using an air-gap its low length (up to 80 μm) means output signal spectrum will be similar to the values standard for a sandwich type transducer with no optical fiber attached. Further increase in gap length causes increase of harmonics of output ultrasonic signal (see. Fig. 6).

5. Conclusion

The work presents the possibilities of transmitting ultrasonic wave in optical fibers through an air-gap. Ultrasonic wave is generated by an ultrasonic sandwich type transducer. Because of dispersion of the optical signal in the air-gap, second optical fiber should be multimode, while first fiber can be either single-mode or multimode. Matlab performed simulations relating to spreading of optical wave in the air-gap show that spreading of the signal and decrease of the amplitude of optical signal at the end of the air-gap are minor (for air-gap length up to 200 μm). The amplitude of the ultrasonic output signal decreases during propagation in the air-gap and it is exponential dependence. For air-gap length over 80 μm ultrasonic signal loss is acceptable. The obtained results will serve as material for further research related to the earlier works [1–5, 20] referred to the analysis of the possibilities of simultaneous transmission of laser radiation and ultrasonic waves in optical fibers.

References

[1] S. Muc, *Archiv. Acoust.* **33**, 619 (2008).

[2] S. Muc, T. Gudra, E. Bereś-Pawlik, *Acta Phys. Pol. A* **116**, 359 (2009).

[3] T. Gudra, S. Muc, *Archiv. Acoust.* **32** (Supplement), 117 (2007).

[4] S. Muc, *Archiv. Acoust.* **34**, 735 (2009).

[5] S. Muc, T. Gudra, E. Bereś-Pawlik, *Archiv. Acoust.* **34**, 697 (2009).

[6] K. Designer, K. Liebold, J. Helfmann, T. Stein, G. Müller, *Neurol. Res.* **21**, 84 (1999).

[7] J. Tschepe, K. Desinger, J. Helfmann, M. Herrig, G. Miiller, in: *Proc. IEEE Ultrason. Symp.*, IEEE, Cannes 1994, p. 1899.

[8] K. Desinger, J. Helfmann, T. Stein, G. Muller, *Proc. SPIE* **2922**, 268 (1996).

[9] V.P. Zharov, A.S. Latyshev, *Proc. SPIE* **3590**, 66 (1999).

[10] K. Desinger Helthiann, T. Stem, K. Liebold, G. Muller, *Proc. SPIE* **3249**, 94 (1998).

[11] V. Bhatia, K. Murphy, R.O. Claus, M.E. Jones, J.L. Grace, T.A. Tran, J.A. Greene, *Meas. Sci. Technol.* **58**, 7 (1996).

[12] Y. Jiang, S. Pang, *Int. J. Infrared Multimeter Waves* **18**, 2375 (1997).

[13] N. Singh, S.C. Jain, A.K. Aggarwal, R.P. Bajpai, *Res. Curr. Sci.* **86**, 309 (2004).

[14] N. Sathitanon, S. Pullteap, *Int. J. Comput. Sci. Eng.* **2**, 63 (2008).

[15] C.A. Achmid, M.S. Miller, G.P. Carmen, K.A. Murphy, R.O. Claus, in: *Proc. IEEE*, IEEE, Charlotte 1993, p. 4.

[16] B. Yu, D.W. Kim, J. Deng, H. Xiao, A. Wang, *Appl. Opt.* **42**, 3241 (2003).

[17] G. Konieczny, Z. Opilski, T. Pustelny, A. Gacek, P. Gibinski, R. Kustosz, *Acta Phys. Pol. A* **118**, 1183 (2010).

[18] J. Leng, A. Asundi, *Smart Mater. Struct.* **8**, 222 (1999).

[19] S.-H. Kim, J.-J. Lee, D.-S. Kwon, *Meas. Mater. Struct.* **10**, 736 (2001).

[20] T. Gudra, S. Muc, *Eur. Phys. J. Special Topics* **154**, 85 (2008).