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A Study of Interaction of Ultrasonic and Optical Wave in Optical Fiber Using the Air Gap

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There exist some possibilities for simultaneous delivery of laser radiation and ultrasounds of low frequency and high intensity: introducing ultrasound oscillations in the optical fiber by the rigid connection of the fiber to the vibrating element and non-contact influence of the ultrasonic wave on the laser beam. The article presents the results of Matlab simulations and experimental studies of influence of the ultrasonic wave on the laser beam. A role of the air gap, and its influence on laser-ultrasonic transmission in optical fiber was examined. Advantages and disadvantages of both solutions of interaction of ultrasonic and optical waves in, e.g., surgical applications are discussed.

Keywords: transmission of acoustic wave, transmission of optical wave, optical fiber, air gap.

1. Introduction

There are two possibilities of influence of the low frequency, high intensity ultrasonic wave on a laser beam: the introduction of ultrasonic oscillations to the optical fiber through the rigid connection between the oscillating element and the fiber optics cable (Muc, 2008; 2009; Muc *et al.*, 2009a; 2009b; Gudra, Muc, 2007; Muc, Gudra, 2011) and the non-contact influence of the ultrasonic wave on a laser beam.

In both cases the ultrasonic wave generates periodic compression and expansion of the medium in the core that the light wave "sees" as a periodic change of the refraction index. The result is the equivalent of a Bragg grating with a "grain" equal to the vibration amplitude of the end of the transformer and the optical fiber. Periodic change of the refraction index in optical fiber caused by ultrasonic wave is visually presented in Fig. 1.

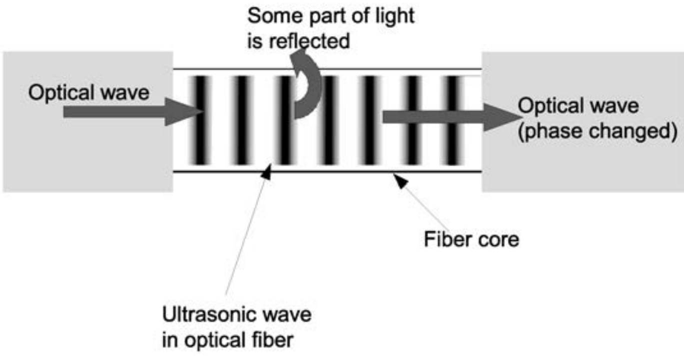


Fig. 1. Periodic change of the refraction index in optical fiber caused by ultrasonic wave.

Vibrations of the ultrasonic transducer cause stretching (expansion) of the optical fibre, and the change of its length (this also results in the change of the refraction index) causing the phase shift of the signal; the phase modulation of the laser radiation is possible (De Paula, Moore, 1984; Kersey, Dandridge, 1989; Grattan, Megitt, 1995).

An optical phase change $\Delta\varphi$ can be written as follows (De Paula, Moore, 1984; Kersey, Dandridge, 1989; Grattan, Megitt, 1995; Kaczmarek, 2006; Wild, Hinckley, 2008):

$$\Delta\varphi = \beta\Delta L + L\Delta\beta, \tag{1}$$

where $\beta\Delta L$ is the phase shift produced by the change in the fiber length, and $L\Delta\beta$ corresponds to the shifts produced by the change in the propagation constant and may be expanded as (Grattan, Megitt, 1995; Kaczmarek, 2006):

$$L\Delta\beta = L\frac{\mathrm{d}\beta}{\mathrm{d}n}\Delta n + L\frac{\mathrm{d}\beta}{\mathrm{d}(2r)}\Delta(2r), \tag{2}$$

where r is the core diameter.

The first term on the right-hand side of the Eq. (2) presents the change of the propagation constant caused by change of the refraction index, while the second one presents the change in mode propagation constant in response to the change in size of the core of the optical fiber. The second term is definitely smaller than the first one and can be ignored. The phase shift can be written as (De Paula, Moore, 1984; Kaczmarek, 2006):

$$\Delta\varphi = \beta\Delta L + L\frac{\mathrm{d}\beta}{\mathrm{d}n}\Delta n, \tag{3}$$

which can also be written as:

$$\Delta\varphi = \frac{2\pi}{\lambda}\left[n\Delta L + L\Delta n\right], \tag{4}$$

where ΔL is the change of the length of the optical fiber, and Δn is the change of the refraction index.

Equation (4) after the consideration that the change of the length is caused by the strain can also be written as (Roe *et al.*, 1996; De Paula, Moore, 1984):

$$\Delta\varphi = k\left[nLe_3 + L\Delta n\right], \tag{5}$$

where e_3 represents longitudinal strain, and k is the optical wave number.

The first term of the Eq. (5) represents the change of the length given by the axial strain e_3 (where subscript 3 refers to the longitudinal axis), while the second one represents the change of the refractive index.

From the Eq. (5) one can write the equation showing the relationship between the light refraction index and the elongation factor that can be depicted in the form (Roe *et al.*, 1996):

$$\Delta\left(\frac{L}{n^2}\right) = \sum P_{ij}S_j = -\frac{2\Delta n}{n^3}, \tag{6}$$

where P_{ij} is the photo-elasticity factor, n is the light refraction index, L is the length of the optical fiber, and S_j is the deformation tensor component defined as (Ziętek, 2004):

$$\begin{aligned}
S_1 &= \frac{\partial u}{\partial x} = S_{xx},\\
S_2 &= \frac{\partial v}{\partial y} = S_{yy},\\
S_3 &= \frac{\partial w}{\partial z} = S_{zz},\\
S_4 &= \frac{\partial v}{\partial z} + \frac{\partial w}{\partial y} = S_{yz} = S_{zy},\\
S_5 &= \frac{\partial u}{\partial z} + \frac{\partial w}{\partial x} = S_{xz} = S_{zx},\\
S_6 &= \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} = S_{xy} = S_{yx},
\end{aligned} \tag{7}$$

where volumes u, v, w are deformations along axes x, y, z.

The phase shift in the optical fiber resulting from elongation can be put into the following equation (Roe *et al.*, 1996; De Paula, Moore, 1984):

$$\Delta\varphi = \frac{knL(e_3 - n^2)}{2(P_{11}e_1 + P_{12}e_2 + P_{12}e_3)}, \tag{8}$$

where e_1, e_2, e_3 represent main elongation factors, P_{11} and P_{12} are photo-elasticity factors, and k is the optical wave number.

Periodic change of the refraction index in a medium during harmonic tension oscillations can be expressed as (Ziętek, 2004):

$$\Delta n = -\frac{n^3}{2} P_{11} S_0 \cos(\Omega t - k_s z), \tag{9}$$

where S_0 is the maximum amplitude of the deformation caused by a sound wave, Ω is the frequency of the acoustic wave, and k_s is the length of the wave vector (propagation constant of the acoustic wave).

In case of introduction of ultrasonic oscillations to the optical fiber through the rigid connection between the oscillating element and the optical fiber depicted in Fig. 2 the following phenomena occur:

- phase modulation caused by changes to the refraction index,
- oscillation of the optical fiber tip.

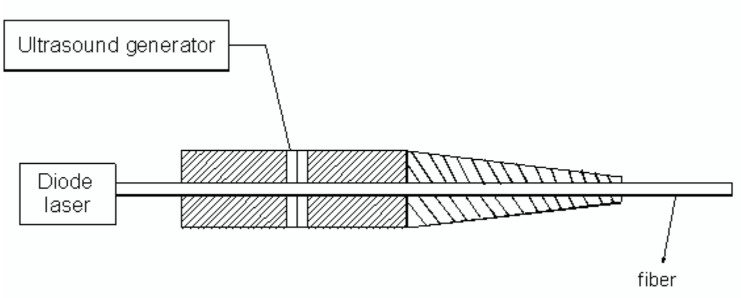


Fig. 2. Diagram of the set-up when introducing ultrasonic oscillation to the optical fiber through the rigid connection between the oscillating element and the optical fiber.

The use of the non-contact influence has been described in papers (Designer *et al.*, 1996; 1998; 1999; Tschepe *et al.*, 1994; Zharov, Latyshev, 1999). However, there is a lack of details regarding the role of the air gap and the way of interaction between these two kinds of energy. The air gap is used in fiber optic sensors (Bhatia *et al.*, 1996; Jang, Pang, 1997; Singh *et al.*, 2004; Sathitanon, Pullteap, 2008; Achmid *et al.*, 1993; Yu *et al.*, 2003; Leng, Asundi, 1999; Kim *et al.*, 2001). These fiber optic sensors are named EFPI (Extrinsic Fabry–Pérot Interferometric sensors). In these sensors the second fiber is the reflecting fiber.

In the literature the Transmission-Type Extrinsic Fabry–Pérot Interferometric optical fiber sensor (Yu *et al.*, 2003; Leng, Asundi, 1999; Kim *et al.*, 1999; 2001) and Transmission/Reflection-Type Hybrid Extrinsic Fabry–Pérot Interferometric optical fiber sensor (Kim, Lee, 2003; 2005) were described;

Non-contact interaction between the ultrasonic and optical waves is analogous to the way of the rule of the Transmission-Type Extrinsic Fabry–Pérot Interferometric optical fiber sensor. In this case the second optical fiber is not a reflecting fiber, but the optical wave is introduced to this optical fiber.

Figure 3 shows the diagram of the assembly for a non-contact interaction between the ultrasonic and optical waves. One fiber connected to the laser diode goes through the hole made in the power transducer and the velocity transformer. At the end of the velocity transformer there is an air gap, to which the fiber optics cable from the laser diode is fed, and another optical fiber is at the output that can interact with a structure (e.g., biological).

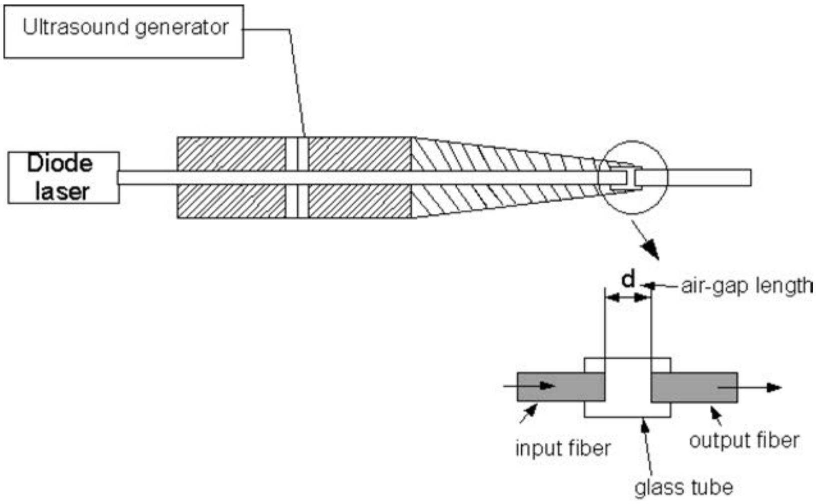


Fig. 3. Diagram of the assembly for a non-contact interaction between the ultrasonic and optical waves.

During vibration of the power sandwich ultrasonic transducer, the optical wave becomes deformed. The endings of optical fibers placed in a glass capillary undergo flattening (the axis of both optical fibres will not be parallel) (Leng, Asundi, 1999). Change of the length of the air gap between two ends of optical fibers causes modulation of the current of the optical output signal. This modulation is sinusoidal with getting a smaller amplitude with the growth of the length of the air gap (Singh *et al.*, 2004).

During the non-contact interaction the following effects occur: phase modulation, amplitude modulation, and oscillation of the tip of the other optical fiber.

Additionally, there is an amplitude loss caused by the air gap that depends both on the gap length and the signal dispersion in the gap (Kim *et al.*, 2001). Part of the light is reflected from the surface of the output optical fiber. Therefore, two optical wave propagation paths result in this optical fiber (Kim *et al.*, 2001).

Equations relating to the optical wave can be written as follows (Kim, Lee, 2005):

$$\begin{aligned} E_1(x_1) &= E_0 L_1(d) t_1 t_2 \cos(kx_1 - \omega t), \\ E_2(x_2) &= E_0 L_2(d) t_1 t_2 r^2 \cos(kx_2 - \omega t), \end{aligned} \tag{10}$$

where E_0 is the amplitude of the optical electric input field, t_1 is the optical fiber I/air transmission factor, t_2 is the air/optical fiber II transmission factor, r is optical fiber I/air reflection factor, $L_1(d)$, $L_2(d)$ are the amplitude losses induced by light spreading in the air gap (two paths), and k is the propagation constant.

Amplitude transmission losses in the air gap along with the phase modulation can be described as follows:

$$T(d) = t_1^2 t_2^2 L_1^2(d) + r^4 L_2^2(d) + 2r^2 L_1(d) L_2(d) \sin(2kd + \Delta\theta \sin \omega_m t). \tag{11}$$

The amplitude of the modulated signal decreases with the increase of the distance between optical fibers.

Two cases can be considered in respect to signal dispersion:

- input and output optical fibers are multi-mode (and the second fiber shall have a larger core diameter in order to facilitate the introduction of the dispersed optical wave),
- input optical fiber is single-mode, and the output one is multi-mode.

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 a larger diameter in order to facilitate the input of the optical wave. In the case of the use of the single mode fibers the formula for the intensity loss by spreading of light is expressed as follows (Seo *et al.*, 2002):

$$\eta(d_p) = L^2(d_p) = \frac{1}{1 + (0.5 d_p / x_R)^2}, \tag{12}$$

where d_p is the path length of light in the air gap, and x_R is the Rayleigh distance which can be expressed by (Kim *et al.*, 1999):

$$x_R = \pi n \omega_0^2 / \lambda, \tag{13}$$

where ω_0 is the spot size at the end face of the optical fiber, and n is the refractive air index, equal to 1.

The spot size at the distance x from the end face in the core axis direction can be written as follows (Kim *et al.*, 1999):

$$\omega(x) = \omega_0 \sqrt{1 + (x/x_R)^2}. \tag{14}$$

Equation (14) represents the scatter of the optical wave at the end face of the optical fiber.

2. Matlab simulation

Simulations were made in the Matlab application in order to see how the air gap length influences the optical wave (Fig. 4). The length of the light in simulations was 808 nm. For the air gap length of 200 μm the amplitude losses were minimal. A 500 μm length of the air gap caused a ca. 20% falldown of

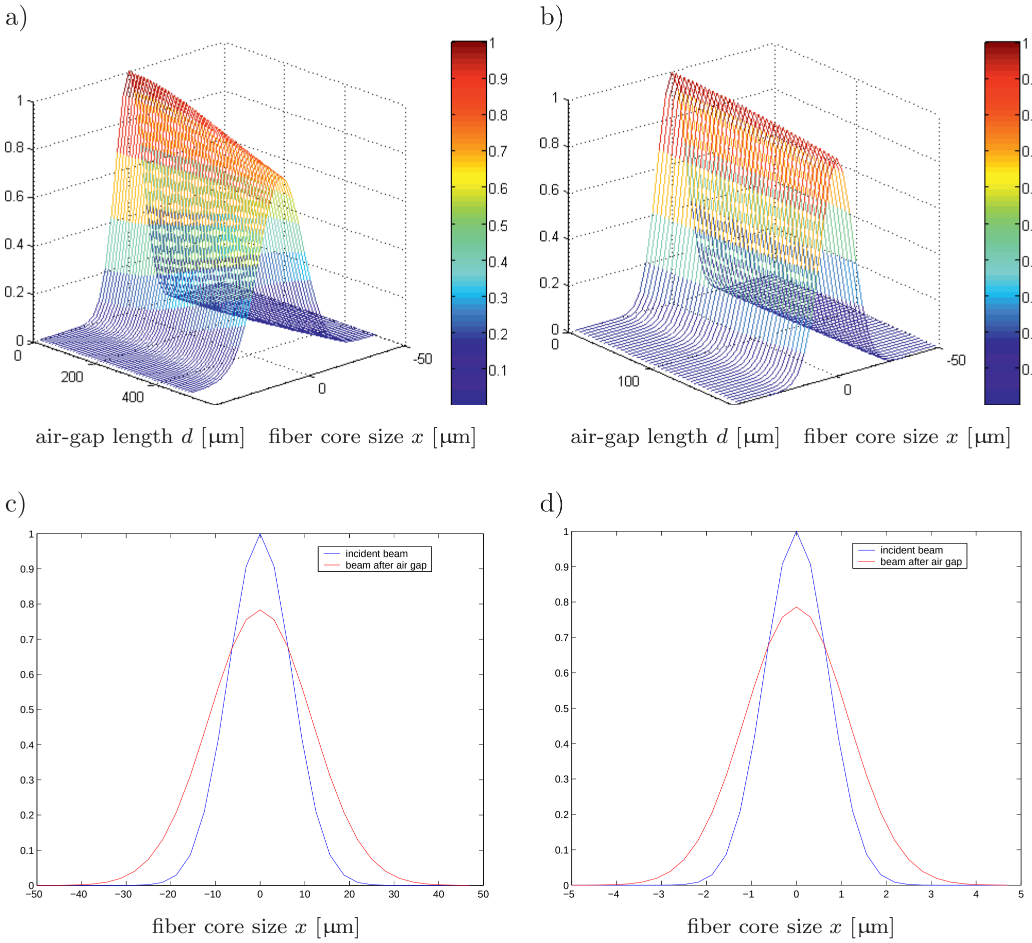


Fig. 4. Influence of the air-gap length on the intensity of the optical wave: a) 3D chart, gap = 500 μm, optical fiber core diameter = 100 μm, b) 3D chart, gap = 200 μm, optical fiber core diameter = 100 μm, c) 2D chart, gap = 500 μm, core diameter = 100 μm, d) 2D chart, gap = 500 μm, core diameter = 10 μm.

the signal's amplitude and the dispersion of the optical signal was considerable (Fig. 4a, c, d).

3. Experimental research

3.1. Influence of the air gap on the ultrasonic wave

Experimental research has been done regarding the influence of the air gap length on the ultrasonic wave propagated in the optical fiber. A capacitive sensor was used to register the output ultrasonic signal at the end of the fiber.

A sandwich type transducer operates with frequency 37.5 kHz. Gluing the optical fiber to the end of the velocity transformer causes a shift of the resonant frequency towards lower frequencies, as depicted in Fig. 5.

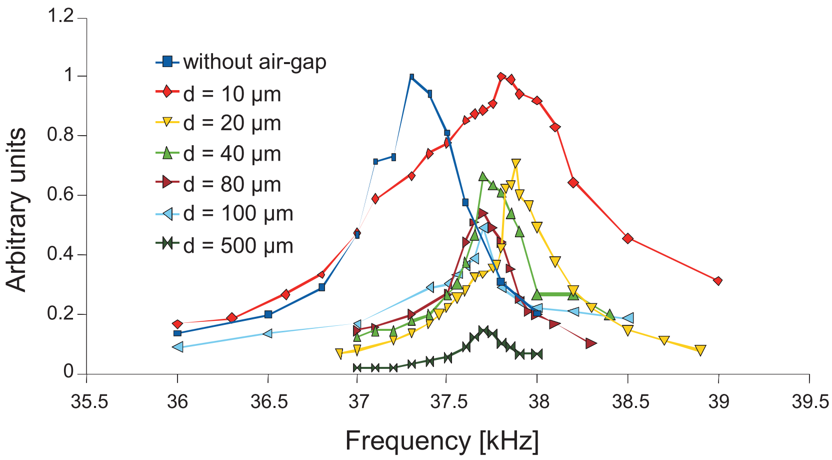


Fig. 5. Dependence of the ultrasonic signal amplitude on the frequency for different lengths of the air gap.

Applying the air gap causes the frequency to shift towards higher values (see Fig. 5). Additionally, it can be observed that the amplitude of the input ultrasonic signal decreases exponentially with the increase of the air gap length. This considerable decrease of the ultrasonic signal amplitude is caused by a high attenuation of the ultrasonic wave in the air.

Gluing of the optical fiber results in harmonics of the input signal. When using short air-gap lengths (up to 80 μm) the spectrum of the input signal is the same as for the transducer without the optical fiber glued, as shown in Fig. 6. Further increase of the gap length results in increase of harmonics of the input signal.

Along with the increase of the output signal power the nonlinear effect has been observed during the propagation of the ultrasonic wave in the optical fiber that resulted in fluctuations of the input signal. Without the optical fiber glued, the fluctuations of the input signal measured at the end of the velocity transformer cannot be observed until power supplied to the transducer is $P = 9$ W. The longer the optical fiber glued to the end of the velocity transformer, the less power supplied to the sandwich type transducer is required to observe fluctuations of the input signal (Fig. 7). For the optical fiber with a 15 cm length without the air gap, the fluctuations of the ultrasonic input signal can be already observed for 1 W.

When using the air gap, the longer it is, the more power has to be supplied to the power transducer in order to obtain the nonlinear effect (Fig. 8).

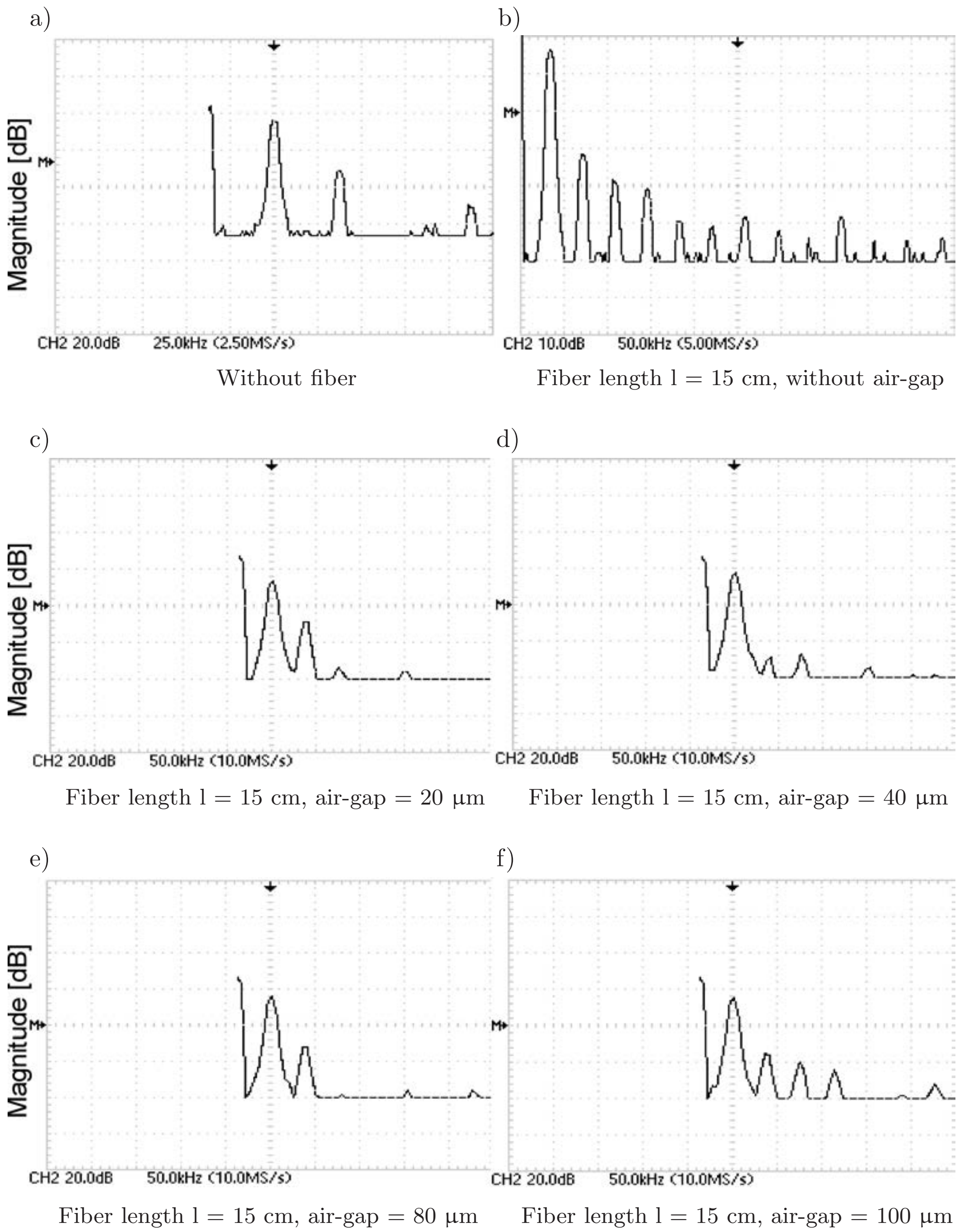
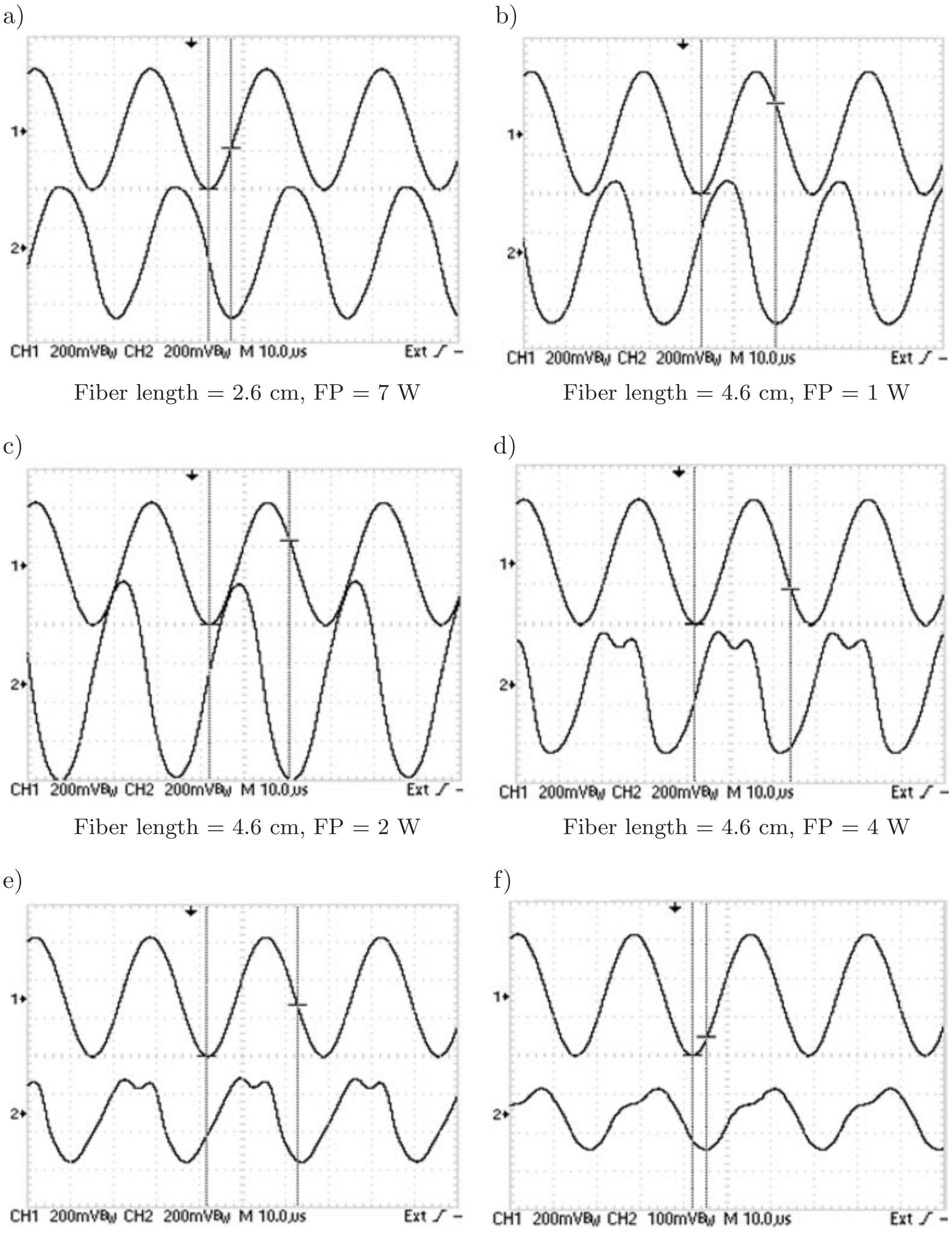


Fig. 6. Ultrasonic output signal spectrum: a) sandwich transducer without a fiber, b) after attaching an optical fiber, without the air gap, c) after attaching an optical fiber with an air gap = 20 μm, d) after attaching an optical fiber with an air gap = 40 μm, e) after attaching an optical fiber with an air gap = 80 μm, f) after attaching an optical fiber with an air gap = 100 μm.



a) Fiber length = 2.6 cm, FP = 7 W

b) Fiber length = 4.6 cm, FP = 1 W

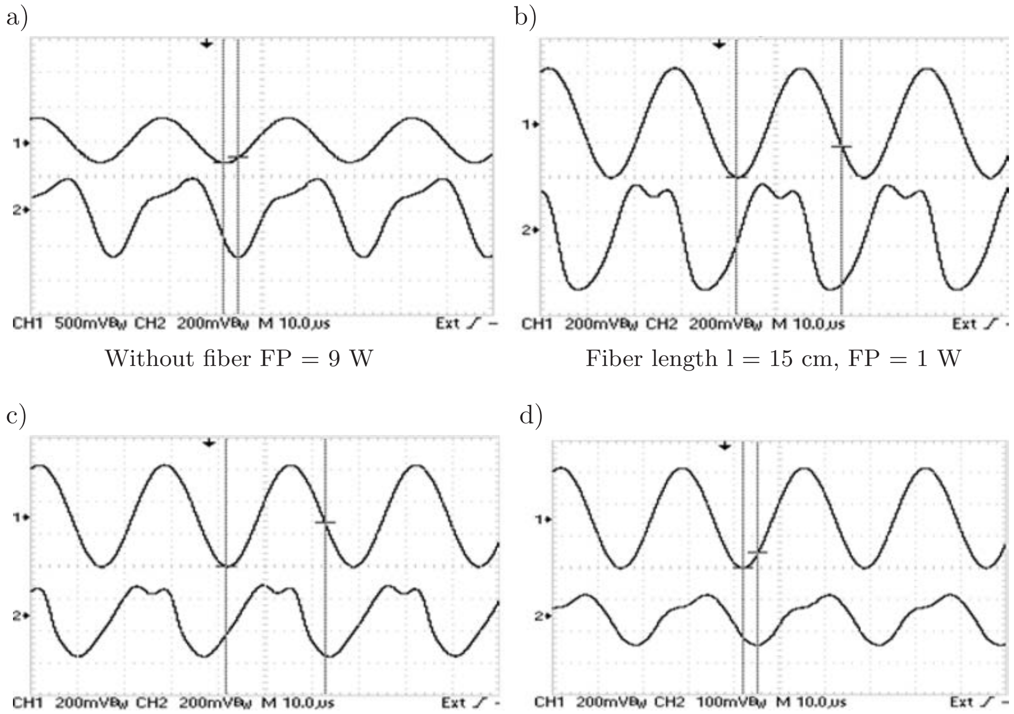
c) Fiber length = 4.6 cm, FP = 2 W

d) Fiber length = 4.6 cm, FP = 4 W

e) Fiber length = 4.6 cm, FP = 9 W

f) Fiber length = 7.7 cm, FP = 1 W

Fig. 7. Dependence of the input signal shape on the optical fiber length and power supplied to the transducer: a) fiber length = 2.6 cm, FP = 7 W, b) fiber length = 4.6 cm, FP = 1 W, c) fiber length = 4.6 cm, FP = 2 W, d) fiber length = 4.6 cm, FP = 4 W, e) fiber length = 4.6 cm, FP = 9 W, f) fiber length = 7.7 cm, FP = 1 W; FP (Forward Power).



a) Without fiber FP = 9 W; b) Fiber length l = 15 cm, FP = 1 W; c) l = 15 cm, $d = 40$ µm, FP = 4 W; d) l = 15 cm, $d = 80$ µm, FP = 7 W

Fig. 8. Dependence of the shape of the ultrasonic input signal on the air-gap length and power supplied to the transducer: a) sandwich transducer without a fiber, b) fiber length = 15 cm, FP = 1 W without an air-gap, c) fiber length = 15 cm, air-gap = 40 µm, FP = 4 W, d) fiber length = 15 cm, air-gap = 80 µm, FP = 1 W; FP (Forward Power).

3.2. Influence of the air gap on the combined laser-ultrasonic transmission

Experimental research has been also done regarding the influence of the air gap on the laser-ultrasonic transmission in the optical fiber. Figure 9 shows the waves output on the oscilloscope. The oscilloscope screen shows only the variable component of the signal resulting from the stimulation of the circuit with an ultrasonic frequency signal. Figure 10a shows the dependence of the output optical signal on the diode power for different air-gap lengths, and Fig. 10b shows the dependence of the ultrasonic output signal amplitude on power supplied to a sandwich type transducer for different air-gap lengths.

Dependence of the amplitude on the air gap between two fibers for various powers supplied to a sandwich type transducer is presented in Fig. 11. From Fig. 11 it results that with the growth of the air gap the amplitude of a signal gets smaller and it is an exponential dependence. Additionally, one can notice that amplitude grows together with the growth of the power delivered to the sandwich power ultrasonic transducer.

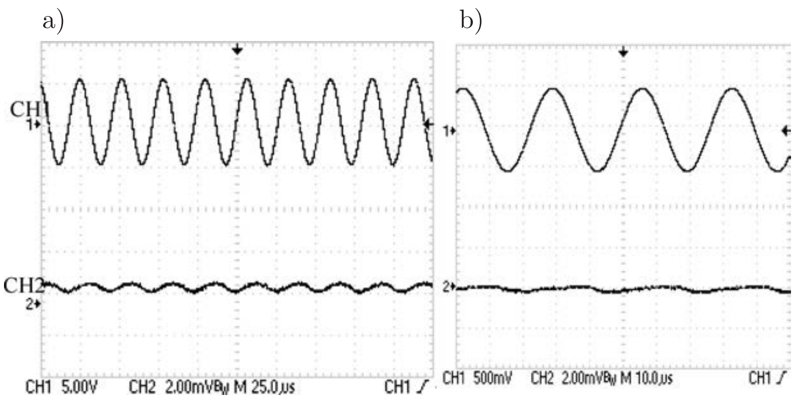


Fig. 9. Waves obtained on the oscilloscope screen for power supplied to the transducer P = 4 W: a) without using the air gap, b) after using the air gap, CH1 is the ultrasonic input signal, and CH2 is the ultrasonic output signal (variable component of the signal).

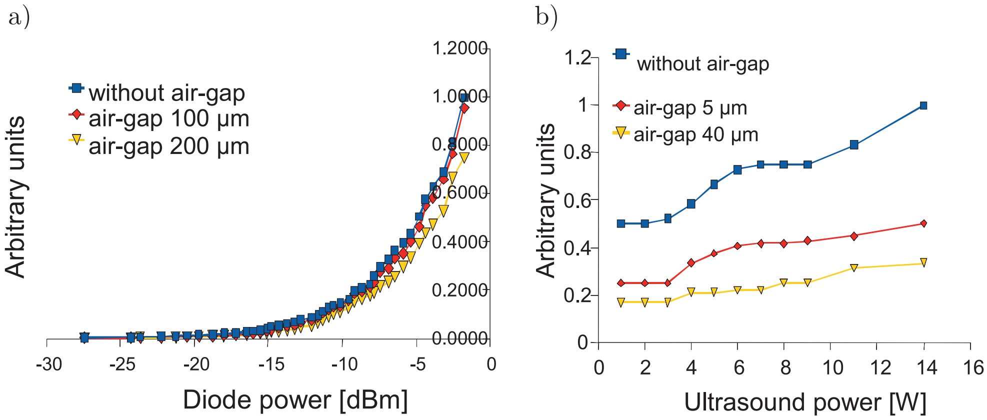


Fig. 10. Dependence of the output signal amplitude: a) optical on the diode power, b) laser-ultrasonic on the power supplied to a sandwich type transducer for different air-gap lengths.

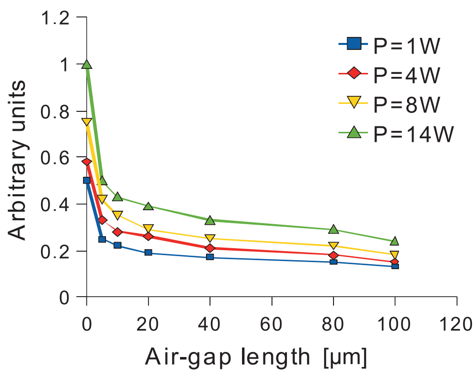


Fig. 11. Dependence of the amplitude on the air gap between two fibers for various powers supplied to a sandwich type transducer.

The output signal amplitude increases with the increase of power supplied to the power transducer. Increase of the air-gap length causes a small decrease in the amplitude of the output optical signal but a significant decrease of the ultrasonic signal amplitude.

Also, the influence of the air gap on the laser-ultrasonic input signal was observed, similarly to the case of the ultrasonic wave only. In this case, using the air gap causes smaller changes in spectrum as compared to the method with a rigid connection (see Fig. 12).

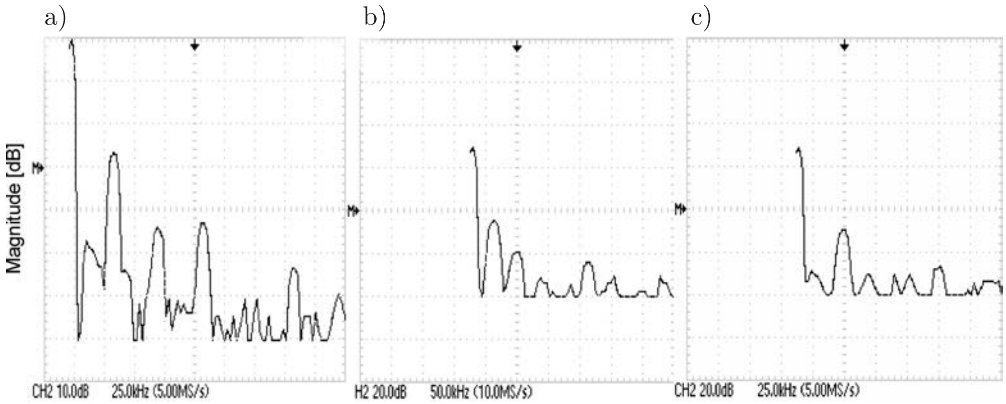


Fig. 12. Output signal spectrum: a) without the air gap, b) after using the 40 μm air gap, c) after using the 10 μm air gap.

Table 1 shows the comparison of the two methods of simultaneous transmission of the laser beam and ultrasonic waves in the optical fiber.

Table 1 shows that using the solution with the air gap, even though difficult to implement, seems to be better due to smaller fluctuations of the input signal and

Table 1. Comparison of methods of simultaneous transmission of the laser beam and ultrasonic waves in the optical fiber.

Rigid connection	Air gap
Simpler implementation (+)	Difficulties in central setting of optical fibers and introducing of the optical wave into the second optical fiber (−)
Fluctuations of the output signal even for small power supplied to the transducer (−)	Fluctuations of the output signal only at high power supplied to the transducer (+)
Change in the signal spectrum (harmonics) (−)	Small changes in spectrum for the air-gap length of 80 μm (+)
Small decrease in the amplitude of both optical and ultrasonic waves (+−)	Decrease of the ultrasonic signal amplitude strongly depends on the air-gap length, a short air gap causes little decrease of both optical and ultrasonic waves (+−)

smaller changes in spectrum for a small air-gap length. Decrease of the output signal amplitude when using the solution with the air gap has drawbacks as well as advantages: there is a small decrease in amplitude for a small air-gap length, but in case of lower optical power there is a lower risk of burning of the optical fiber when using this method, e.g., in cutting biological structures.

4. Conclusion

The article shows the possibility of an acoustic wave transmission in the optical fiber using the air gap. Simulations made in the Matlab application regarding the dispersion of the optical wave in the air gap show that for the air gap of length up to 200 μm the dispersion of signal and decrease of its amplitude at the end of the gap are small.

Due to dispersion of the optical signal in the air gap, the second optical fiber should be multi-mode, while the first one can be either single- or multi-mode. Due to the thickness of the fiber used in surgery, only multi-mode optical fibers are suitable, moreover, the second fiber should have a core of larger diameter in order to facilitate the input of the optical wave. The amplitude of the output signal decreases during propagating in the air gap and it is an exponential dependence.

Experimental research of the influence of the air gap on the ultrasonic signal shows that losses of the ultrasonic signal are acceptable for the air-gap length of 80 μm. The solution using a‘ short air gap seems to be better. The measurements show that the air-gap length should not be bigger than 80 μm.

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