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Interaction of the ultrasonic wave with the optical wave in optical fiber using the air gap

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ABSTRACT

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 ultrasonic and optical waves in e.g. surgical application are discussed.

INTRODUCTION

There are several 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 [1, 2, 3, 4, 5] and the non-contact influence of the ultrasonic wave on a laser beam.

In both cases the ultrasonic wave generates periodic compression and rarefaction 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.

The equation that shows the relationship between the light refraction index and the elongation factor can be depicted in the form [19]:

$$\Delta\left(\frac{L}{n^2}\right)=\sum P_{ij}S_{ij}=-\frac{2\Delta n}{n^3} \tag{1}$$

where P_{ij} – photo-elasticity factor, S_{ij} – deformation tensor component, n – light refraction index, L – length of the optical fiber.

The phase shift in the optical fiber resulting from elongation can be put into the following equation [19, 20]:

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

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

Periodic change of the refraction index in a medium during harmonic tension oscillations can be expressed as [21]:

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

where S_0 – maximum amplitude of deformation caused by a sound wave, Ω – frequency of the acoustic wave, k_s – 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 Figure 1 the following phenomena occur:

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

Using the non-contact influence has been described in publications [6, 7, 8, 9, 10]. However, there is 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 [11, 12, 13, 14, 15, 16, 17, 18].

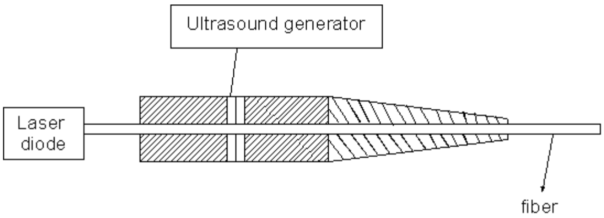


Figure 1. A block diagram of a measurement system when introducing ultrasonic oscillation to the optical fiber through the rigid connection between the oscillating element and the optical fiber

Figure 2 shows the diagram of a block diagram of a measurement system for a non-contact interaction between the ultrasonic wave and the optical wave. 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).

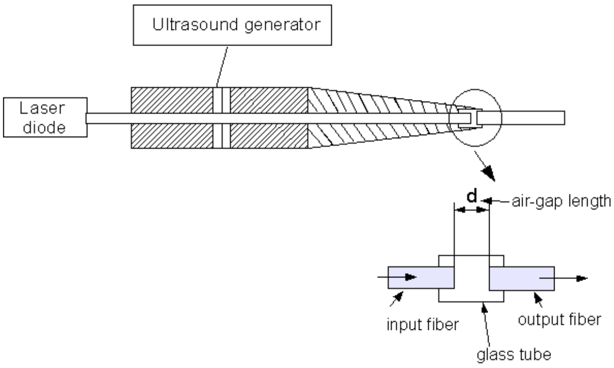


Figure 2. A block diagram of a measurement system for a non-contact interaction between the ultrasonic wave and the optical wave

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 are amplitude losses caused by the air gap that depend both on the gap length and signal dispersion in the gap. 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 [18].

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

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

where t_1 – the optical/air transmission factor, t_2 – the air/optical transmission factor, $L_1(d)$, $L_2(d)$ – amplitude losses induced by light spreading in the air gap (two paths), r – optical fiber/air reflection factor, k – propagation constant.

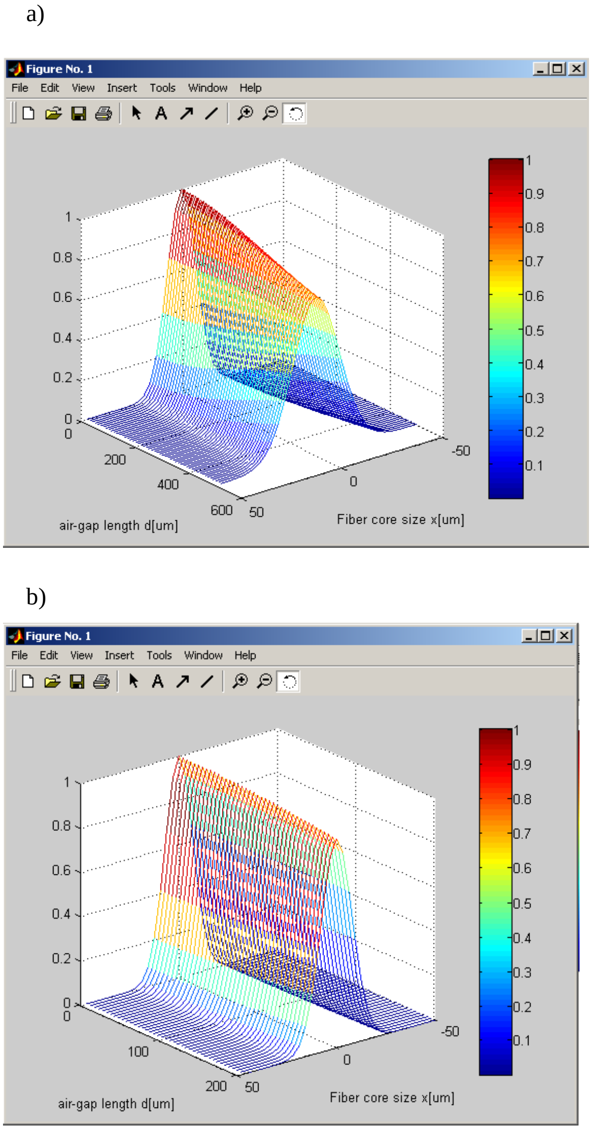
The amplitude of the modulated signal decreases with the increase of distance between optical fibers.

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.

MATLAB SIMULATIONS

Simulations were made in the Matlab application in order to see how the air gap length influences the optical wave (Fig. 3). For the air gap length of 200 µm the amplitude losses are minimal.


a)

b)

Figure 3. Influence of the air gap length on the optical wave, 3D chart, a) gap = 500 µm, optical fiber core diameter = 100 um, b) gap = 200 um, optical fiber core diameter = 100 µm

EXPERIMENTAL RESEARCH

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 sandwich type transducer operates with frequency 37.5 kHz. Gluing the optical fiber to the end of the velocity transformer causes the shift of the resonant frequency towards lower frequencies, as depicted in Figure 4. Applying the air gap causes the frequency to shift towards higher frequencies (Figure 4). Additionally, it can be observed that the amplitude of the input ultrasonic signal decreases with the increase of the air gap length. Amplitude decrease is exponential. Considerable decrease of the ultrasonic signal amplitude is caused by a high attenuation of the ultrasonic wave in the air.

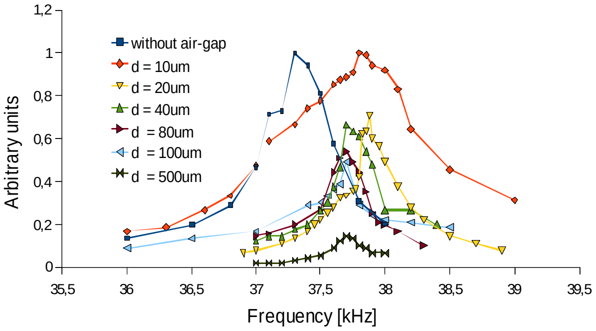
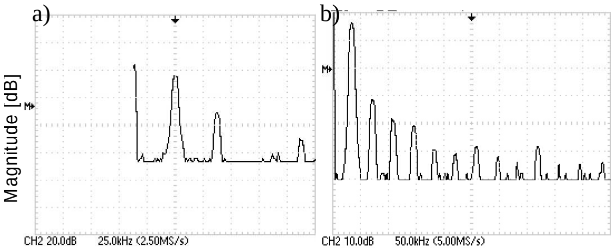


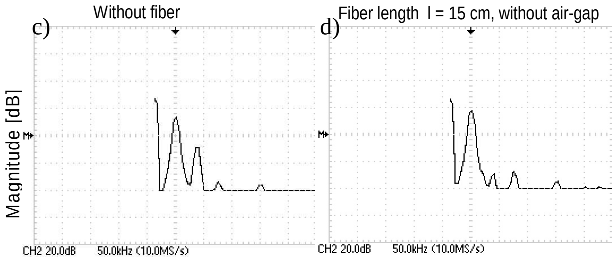
Figure 4. Dependence of the ultrasonic signal amplitude on the frequency for different lengths of the air gap

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 Figure 5). Further increase of the gap length results in increase of harmonics of the output signal.



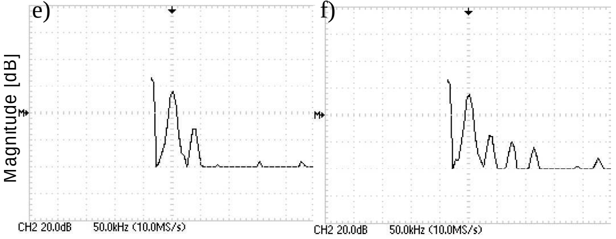
Without fiber

Fiber length l = 15 cm, without air-gap



Fiber length l = 15 cm, air-gap = 20 µm

Fiber length l = 15 cm, air-gap = 40 µm

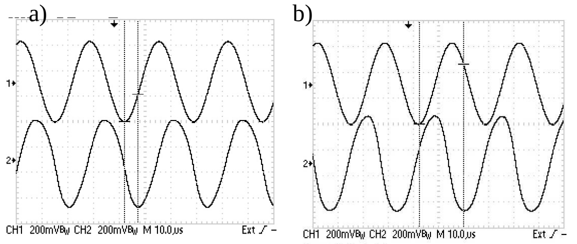


Fiber length l = 15 cm, air-gap = 80 µm

Fiber length l = 15 cm, air-gap = 100 µm

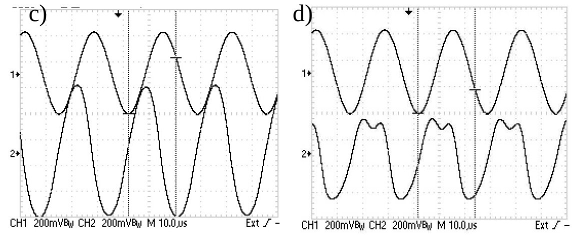
Figure 5. Ultrasonic output signal spectrum, a) a sandwich transducer without a fiber, b) after attaching optical fiber, without air-gap, c) after attaching optical fiber with an air gap = 20 µm, d) after attaching optical fiber with an air gap = 40 µm, e) after attaching optical fiber with an air gap = 80 µm, f) after attaching optical fiber with an air gap = 100 µm

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 output 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 (Figure 6). For the optical fiber length of 15 cm without the air gap, the fluctuations of the ultrasonic output signal can be already observed for P = 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 (Figure 7).



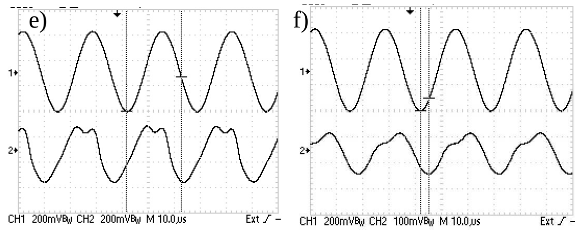
Fiber length = 2,6 cm, FP=7W

Fiber length = 4,6 cm, FP=1W



Fiber length = 4,6 cm, FP=2W

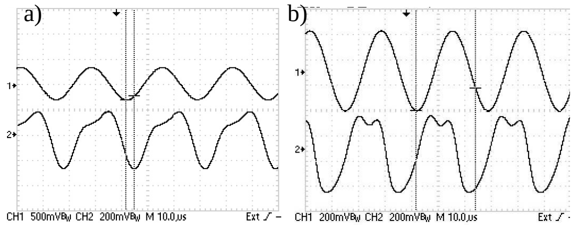
Fiber length = 4,6 cm, FP=4W



Fiber length = 4,6 cm, FP=9W

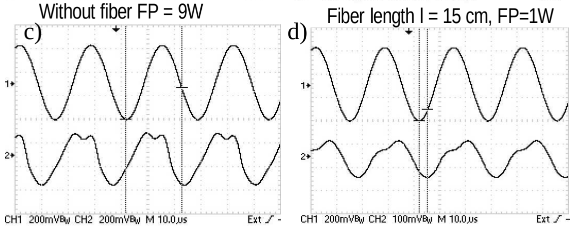
Fiber length = 7,7 cm, FP=1W

Figure 6. Dependence of the input signal shape on the optical fiber length and power supplied to the transducer



Without fiber FP = 9W

Fiber length l = 15 cm, FP=1W



l= 15 cm, d = 40 um, FP = 4W

l=15 cm, d = 80 um, FP = 7W

Figure 7. Dependence of the shape of the ultrasonic output signal on the air gap length and power supplied to the transducer

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 8 shows 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 9a shows the dependency of the output optical signal on the air gap length, and the Figure 9b shows the dependency of the input signal amplitude on power supplied to the sandwich type transducer.

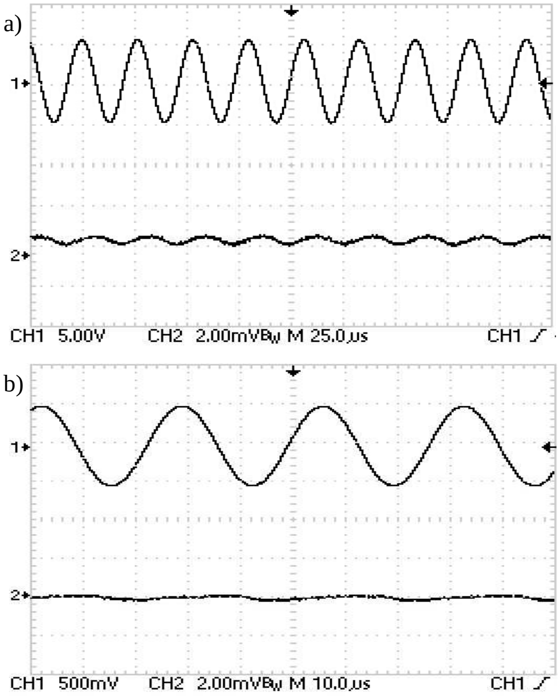


Figure 8. Waves obtained on the oscilloscope screen for power supplied to the transducer P = 4 W, a) without using the air gap, b) after using the air gap, CH1- ultrasonic input signal, CH2 – output signal (variable component of the signal)

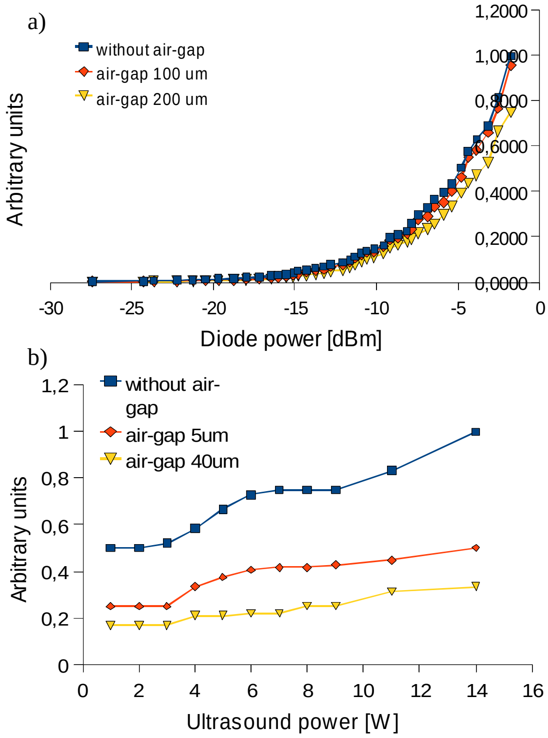


Figure 9. Dependence of the output signal amplitude a) optical on the air gap length, b) laser-ultrasonic on the power supplied to the sandwich type transducer

The output signal amplitude increases with the increase of power supplied to the power transducer. Increase of the air gap length causes little decrease in the amplitude of the output optical signal, but 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. Also in this case, using the air gap causes smaller changes in spectrum as compared to the method with a rigid connection.

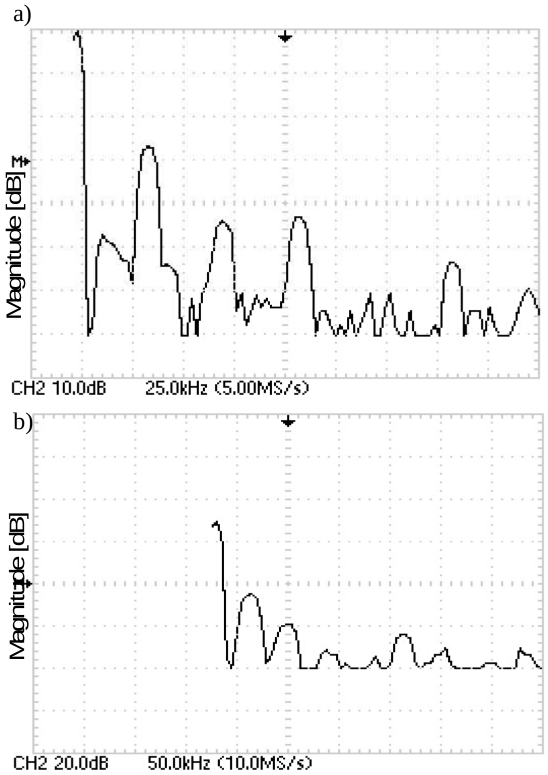


Figure 10. Output signal spectrum, a) without the air gap, b) after using the 40 µm air gap

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. 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 optic 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 amplitude of both optical and ultrasonic wave (+-)	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 wave (+-)

Table 1 shows that using the solution with the air gap, however difficult to implement, seems to be better due to smaller fluctuations of the input signal and 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 little decrease in amplitude for a small air gap length, but in case of lower optical power there is less risk of burning of the optical fiber when using this method e.g. in cutting biological structures.

Conclusion

The work shows the possibility of the 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. Experimental research of the influence of the air gap on the ultrasonic signal show that the 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 be no more than 80 μm.

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