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Transmission of Ultrasonic Waves in Optical Fibers with the use of Sandwich Type Transducer

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Optical fibers are commonly used to transmit laser beams. The possibility of acoustic wave propagation in optical waveguides creates new prospects for simultaneous transmission of laser beams and ultrasonic waves. This combined technology could be useful in e.g. surgical treatment. A comparative analysis of both systems shows that combining the advantages of ultrasounds and laser light in one device, makes it possible to compensate for the faults of each of the technologies and to improve the effectiveness of surgical operations. The article presents the results of experimental studies of transmission of ultrasonic wave in optical fibers using a sandwich-type ultrasonic power transducer. It also presents amplitude characteristics of an ultrasonic signal propagated in an optical fiber. The effect of the length of the fiber on the achieved output signal amplitudes was studied. The relation of the output signal of a capacitive sensor to the power applied to the sandwich-type transducer was presented. The reflected power during ultrasonic wave propagation in an optical fiber was also measured. The measurements of the ultrasonic wave transmission were performed for single-mode and multi-mode step-index optical fibers.

Keywords: ultrasounds, transmission of acoustic wave in an optical waveguide.

1. Introduction

Optical fibers are commonly used to transmit laser beams. The possibility of acoustic wave propagation in optical fibers [3, 4, 7, 10] creates new prospects for simultaneous transmission of laser beams and ultrasonic waves [8, 9]. A comparative analysis of both systems shows that combining the advantages of ultrasounds and laser light in one device makes it possible to compensate for the faults of each of the technologies and to improve the effectiveness of surgical operations [2]. The development of versatile devices in medicine is desired in order to reduce the number of equipment in hospitals. The results of investigations will allow for the selection of suitable optical fiber (the selection of suitable diameter and the suitable length of optical fiber). Examination of the effect of bending of the optical fiber on the propagated ultrasonic wave will allow to answer the question if the bent geometry of optical fibers would be suitable to achieve the effective transfer of ultrasonic energy to the tissue.

Relations involved in acoustic wave propagation in an optical fiber and the acoustic conditions related to guiding acoustic waves in a light pipe are shown in [2–4, 7, 9]. Thanks to the propagation of ultrasonic wave in optical fiber, ultrasounds can be used in laparoscopic and endoscopic surgical operations. Surgery utilizes an ultrasound applicator, equipped with a longitudinally vibrating ultrasonic transducer. A suitable sandwich-type ultrasonic power transducer operating at low frequency was designed to generate longitudinal waves.

2. Measurement system

Initially, research on ultrasonic wave transmission in optical fibers involved using of a piezoelectric plate. An optical fiber, the length of which was the multiple of the ultrasonic wavelength ($\lambda/2$), was glued to the plate in order to achieve maximum output vibration amplitude [7, 8]. The results of the research, during which the plate was replaced with a sandwich-type power transducer were presented. An optical waveguide of adequate length was attached to the end of a conical velocity transformer of a sandwich ultrasonic transducer. The measurement system is shown in Fig. 2. Ultrasonic transducer with a conical velocity transformer was designed by the author and manufactured. It consists of 2 piezoelectric rings (PCM 41 made by Noliac, outside diameter 15.9 mm, inside diameter 7.6 mm, thickness 2.6 mm), clamped between two-end metal pieces by means of a bolt. Backing of a sandwich transducer (thickness 26 mm) is made of steel. The head (thickness 22 mm) and the velocity transformer (thickness 71 mm) are made of aluminum. The diameter of the sandwich transducer is 18 mm and the diameter of the end of the conical velocity transformer is 4 mm.

The characteristics of the transducer are shown in Fig. 1.

The transducer had two resonance frequencies ($f_1 = 37.5$ kHz, $f_2 = 55.8$ kHz). A capacitive sensor was used to register vibrations (Fig. 2). An AG-Series power amplifier by T&C Power Conversion controlled by means of a HP 33120A generator was used during the investigation. An impedance matching transformer SUT 1KLF-5 was also used to match the impedance of a source and that of its load, for the most efficient transfer of energy. A capacitive sensor was used to register longitudinal vibrations. A capacitive sensor is of own production.

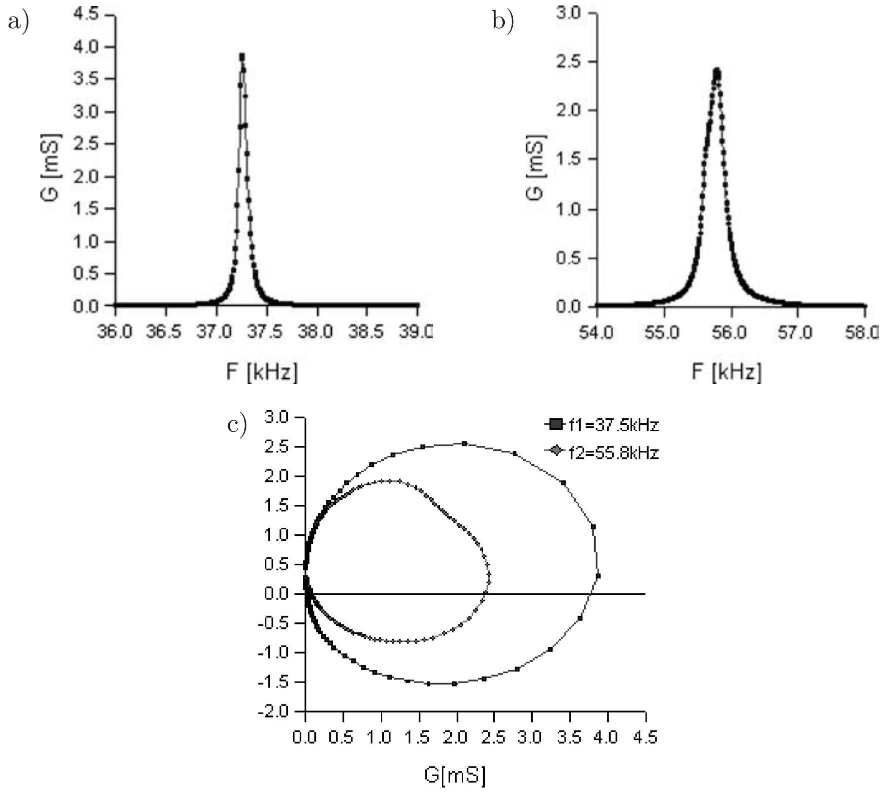

Fig. 1. Sandwich-type power transducer characteristics for $f_1 = 37.5$ kHz, $f_2 = 55.8$ kHz resonance frequencies (a), b) conductance course in a function of frequency, c) amplitude-phase characteristics of the admittance module.

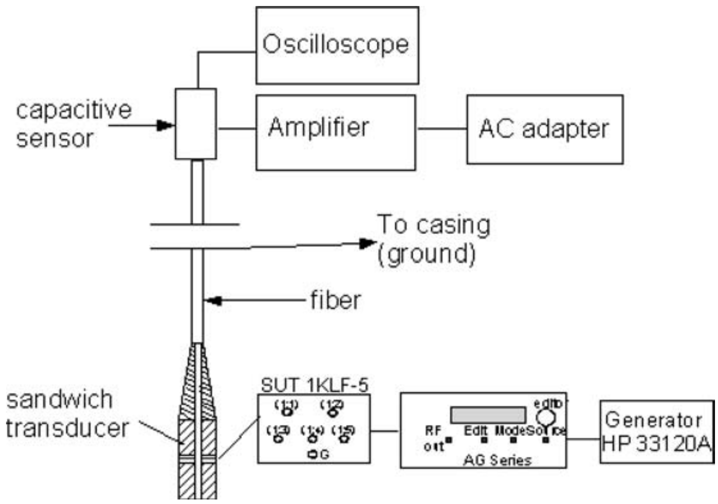

Fig. 2. A block diagram of the system for measuring transmission of acoustic wave in an optical fiber.

3. Study results

The frequency of the vibrations transmitted by the transducer without an optical fiber, using a capacitive sensor, was measured. Since the transducer worked better at the frequency of 37.5 kHz, the amplitude showed by the detector for this frequency is higher than for 55.8 kHz (Fig. 3a). This was followed by additional measurements performed for 37.5 kHz resonance frequency.

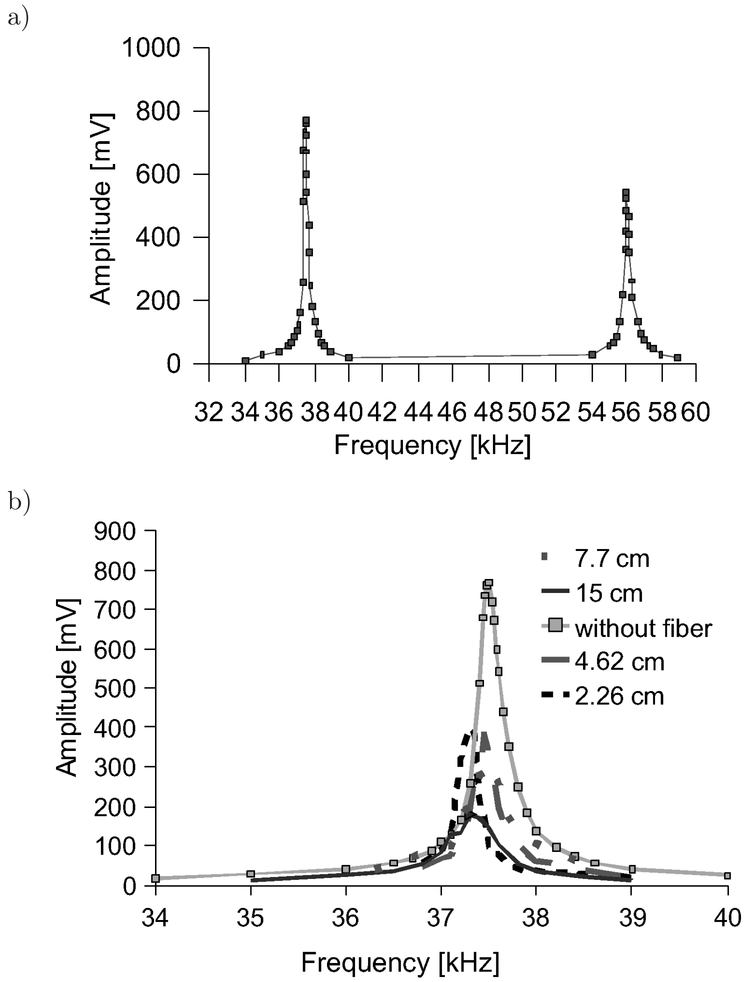

Fig. 3. Amplitude characteristic of displacement of the optical fiber-tip achieved by means of a capacitive sensor: a) transducer without an optical fiber, b) comparison of the amplitudes from the studied fiber lengths.

The measurements were taken for a 1 mm multi-mode optical fiber. The core of the fiber was made of 97% SiO_2, 3% GeO_2 and the cladding – of 100% SiO_2. Properties of these glasses are listed in Table 1.

Table 1. Properties of glasses used in optical fiber [6].

Property	Composition	
	100% SiO_2	97% SiO_2, 3% GeO_2
refractive index n	1.4580	1.4624
density ρ [kg m^{-3}]	2202	2244
Poison's ratio	0.170	0.165
Young's modulus, E [10^{10} dyn/cm^2]	70.70	72.45
longitudinal velocity V_L [m s^{-1}]	5944	5806
transversal velocity V_T [m s^{-1}]	3749	3677

The effect of the length of the fiber on the achieved output signal amplitudes was examined. The lengths of the optical fibers were the multiples of $\lambda/2$. The results were arranged together with the amplitude achieved for a transducer without an optical fiber (Fig. 3b). Attaching of an optical fiber results in slight displacement of the resonance frequency (Table 2) and lower output amplitude.

Table 2. Maximum amplitudes for the studied optical fiber lengths.

f [kHz]	fiber length [cm]	$A_{\max}$ [m V]
37.5	without fiber	768
37.3	15	180
37.5	7.7	312
37.45	4.62	384
37.3	2.26	400

Figure 3b shows that the output signal amplitude decreases together with increasing fiber length. Glass optical fibers must be tightly connected directly to the acoustic transducers due to poor matching of impedance between the transducer and air, and between air and the glass optical fiber. If the fiber is attached carelessly, it may result in a decrease of amplitude. The acoustic loss for pure fused silica is $\alpha/f^2 \cdot 10^{15} = 0.12$ s^{2}m^{-1}, where α is attenuation coefficient [5]. For the frequency of 37.3 kHz, the amplitude attenuation coefficient is $1.66 \cdot 10^{-7}$ [1/m]. Optical fiber attenuation for this frequency is insignificant; therefore the differences in amplitudes for various optical fiber lengths are insignificant.

Figure 4 shows the phase shift relation between the input and output signals. The phase shift changes in cycles. 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 changes in its phase shift. In case of the studied optical fibers, the phase shifts are adjacent to one another and change from 0 to π rad.

Research was performed for 37.3 kHz resonance frequency to observe the relation of the output signal amplitudes from a capacitive sensor to the power applied to the sandwich-type transducer (Fig. 5a) and the reflected power during

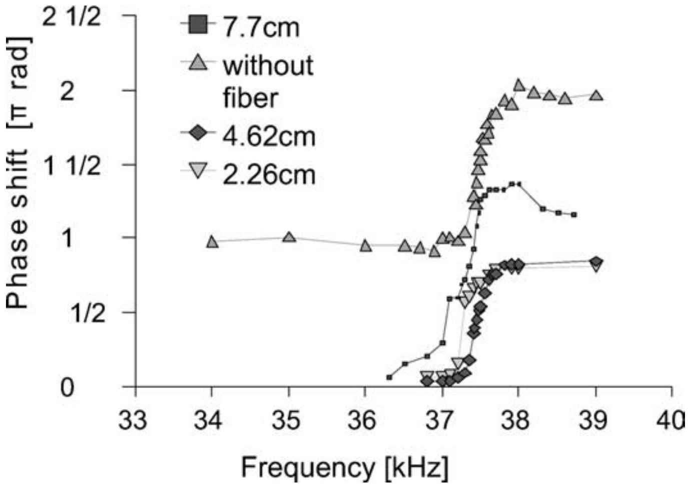

Fig. 4. Phase shift relation between input and output signal.

ultrasonic wave propagation (Fig. 5b). An AG-Series power amplifier by T&C Power Conversion controlled by means of a HP 33120A generator was used during the investigation. A matching transformer was also used.

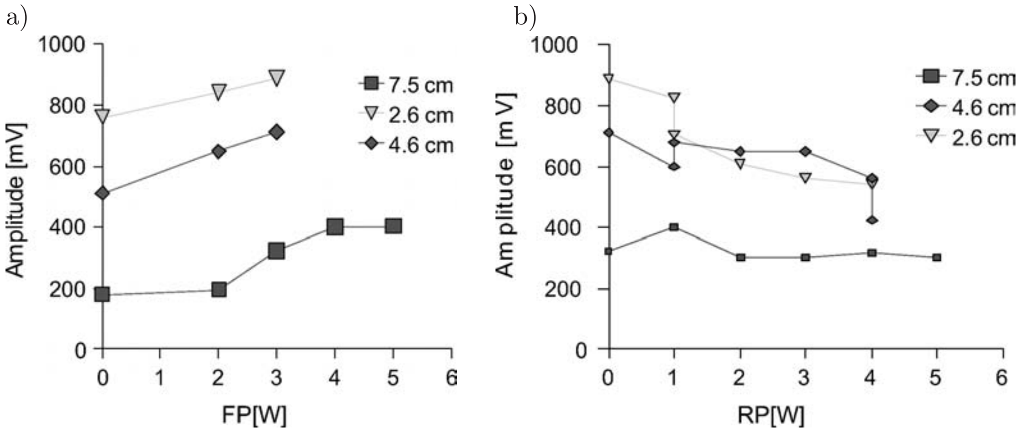

Fig. 5. Relation of the output signal amplitude from: a) power applied to the transducer – FP (Forward Power), b) RP (Reflected Power).

The higher is the power applied to the system, the higher will be the amplitude of the output signal. Increase of the reflected power results in decrease of the amplitude of the output signal.

The effect of bending of an optical fiber (radius = r) was also examined (see Fig. 6a). A single-mode step-index optical fiber was used during the measurements. The core of the fiber is made of 97% SiO2 and 3% GeO_2; the cladding is made of 100% of SiO_2.

The length of the waveguide was 22.7 cm (multiple of the $\lambda/2$). Next, the effect of the length of the fiber and the number of coils on the propagated ultrasonic wave was examined. Block diagram of the measurement system is presented in Fig. 6b.

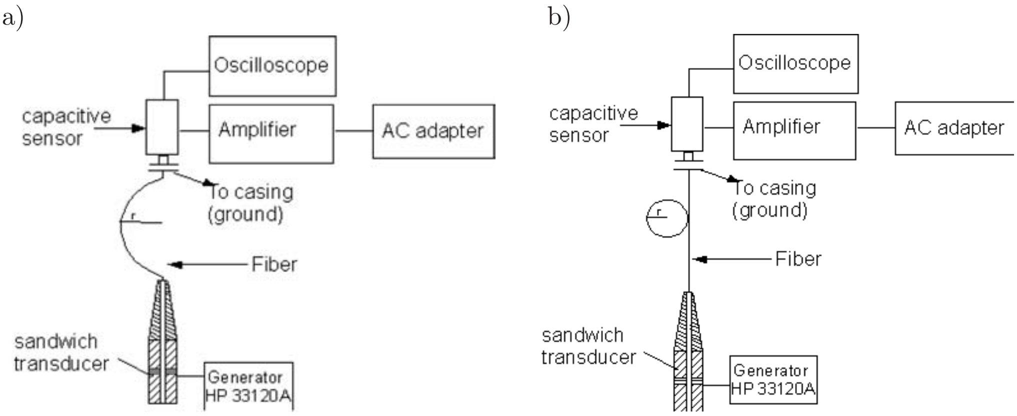

Fig. 6. Block diagram of the measurement system used to observe: a) the effect of bending of an optical fiber, b) the length of the fiber and the number of loops of optical fiber (radius r) on the propagated ultrasonic wave.

The lengths of optical fiber and the number of coils are presented in Table 3.

Table 3. Lengths of optical fibers and number of coils used during the measurement.

fiber length [cm]	number of coils	coil radius [cm]
140	7	2.5
140	6	3.5
115	5	2.5
97	4	2.5
78	3	2.5
59	2	2.5

Figure 7a shows the relation of amplitude to the radius of optical fiber bend. The tighter is the bend of the optical fiber (shorter radius), the lower will be the amplitude. Tighter bend also results in a decrease of the phase shift (Fig. 7b) between the input and output signals. Measurements were conducted for the frequency 37.3 kHz.

The dependence of resonance frequency and amplitude on various radii of optical fiber bend was also examined (Fig. 8). Results are presented in Table 4. Figure 8 shows the amplitude of longitudinal vibrations for radius $r = 1$ cm, $r = 5$ cm, $r = 20$ cm. The bend of optical fiber causes the change of the resonance frequency of the system.

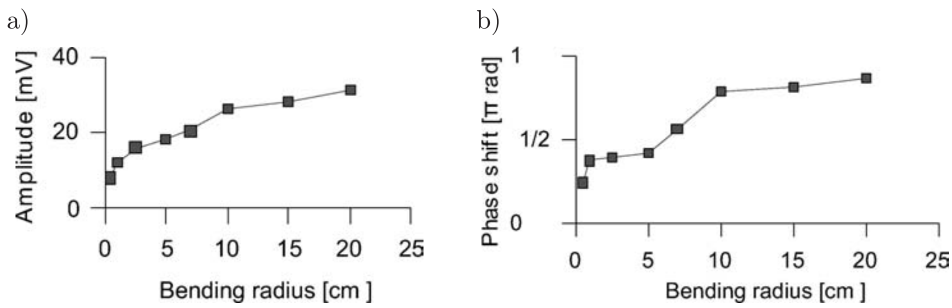

Fig. 7. Relation of: a) amplitude, b) phase shift between the input and output signals, to the radius of optical fiber bend.

Table 4. The dependence of resonance frequency and amplitude for the various radii of optical fiber.

$f = 37.3$ kHz			
r [cm]	A [mV]	$A_{\max}$ [mV]	f [kHz]
0.5	8	10	37.550
1	12	13	37.525
2.5	16	18	37.500
5	18.4	20	37.475
7	20.4	23	37.450
10	26.4	29	37.430
15	28.2	31	37.400
20	31.2	35	37.350

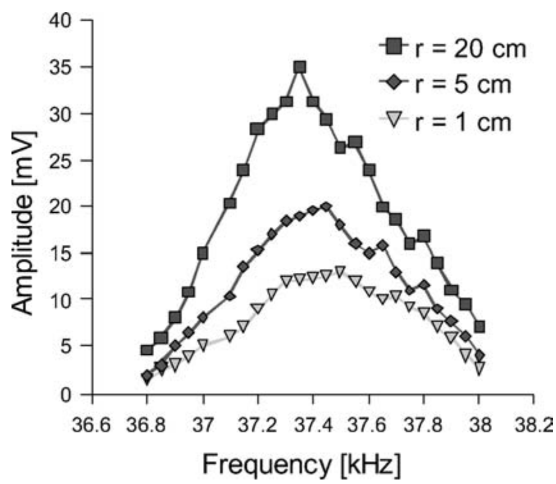

Fig. 8. The dependence of amplitude and frequency for various bending radii of optical fiber.

When the fiber is curved, the longitudinal and flexural waves cannot be propagated independently [12, 13]. Only "longitudinal-flexural" modes can exist. The velocity of the quasi-longitudinal mode in a bent fiber depends on its local curvature and on the frequency. The phase velocity within the bend of the fiber with a bend of constant curvature joined with straight segments remains constant, but is different from the bar velocity. Optical fiber in this way is similar to the straight rod with jump of the phase velocity. Wave reflection or the transformation of the wave may appear during propagation through the bend [1]. The reflection makes difficult the transfer of energy through an optical fiber. The ultrasonic wave can go out of the optical fiber. Reflections leads to the phase shift between the displacement and the stress at the driven end of the fiber. It causes the reduction the acoustic power. The decrease of the amplitude is caused by the losses of transmission on bends (additional attenuation of the ultrasonic wave in optical fibers).

With the growth of the bend of the optical fiber (shorter radius), grows the resonance frequency (Fig. 9).

Figure 10a shows the relation of the number of coils on the fiber and the radius of the coil to the output signal amplitude; the effect on the phase shift is

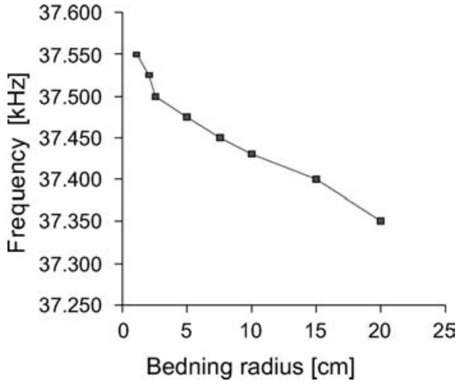

Fig. 9. The dependence of the resonance frequency on the radius of optical fiber bend.

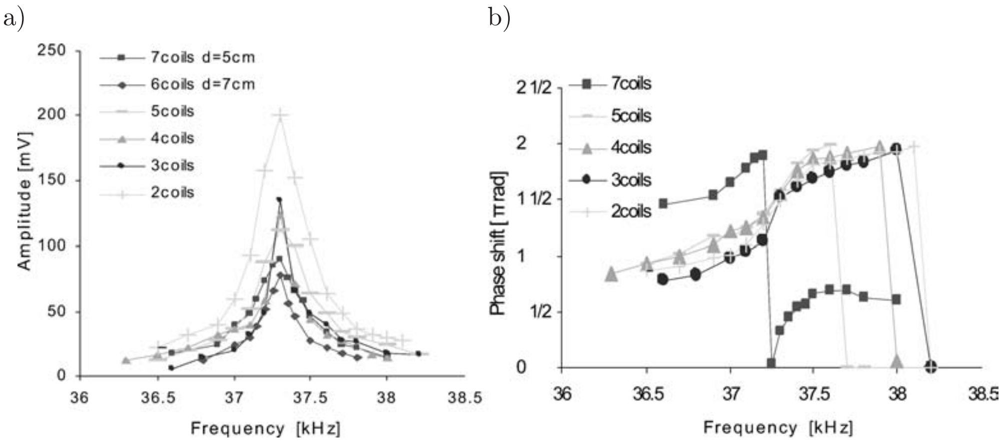

Fig. 10. Relation of: a) output signal amplitude to frequency, b) phase shift between the input and output signals to the frequency. Fiber length and the number of coils are the parameters.

shown in Fig. 10b. The longer is the optical fiber, the lower will be the frequency at which phase shift changes from 2π to 0. For all the studied fiber lengths, the phase shift is similar and changes from 0 to 2π rad. The change in the number of coils results in a shift of frequency for which the phase shift changes from 2π to 0π. The shorter the fiber, the higher the frequency for which this change occurs.

4. Conclusions

The work presents the results of studies on transmission of ultrasonic waves in optical fibers using a sandwich-type ultrasonic power transducer. It presents the relation of the output signal amplitude from a sensor to the length of a glued optical fiber and to the power applied to the transducer. Thanks to the propagation of ultrasonic waves in optical fiber, ultrasounds can be used in laparoscopy and endoscopy surgical operations. Therefore, the effect of bending of the optical fiber on the propagated ultrasonic wave was studied. Attenuation grows with the growth of the bend. Therefore there is some doubt, if the bend geometry of optical fibers would be suitable to achieve the effective transfer of energy to the tissue. When the fiber is placed in an endoscope, the local curvature is small, so attenuation due to bending should not be significant. After analysis of the results obtained, one can conclude that vibrations of the optical fiber depend on the frequency of the signal. The bend of optical fiber influences the resonance frequency. That is why compensating of the resonance frequency becomes essential.

The possibility of acoustic wave propagation through optical fibers allows to use the combination of laser and ultrasounds in one device and one tip, using an optical fiber. Such combined laser-ultrasonic interaction seems to be more effective. A comparative analysis of both systems showed that combining of the advantages of ultrasounds and laser in one device allows us to compensate for the faults of each of the technologies and to improve the effectiveness of surgical operations. The combined method is safer and reduces the risk of complications. The development of versatile devices in medicine is desired in order to reduce the size of equipment in hospitals. Conclusions will be used for further analysis of the possibilities [2] of simultaneous transmission of high-power laser rays and high-power ultrasonic waves in optical waveguides.

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