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Experimental Study of Simultaneous Transmission of Ultrasonic Waves and Optical Radiation via Optical Fiber Couplers

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This article presents the results of experimental studies of simultaneous transmission of ultrasonic waves and laser signals in optical fibers by the use of both the optical single mode and multimode fiber couplers. This work was aimed, among other things, at the study of the way the acoustic energy affects a laser beam. The light wave was guided into one of the coupler's arms. The optical power applied to one input of the coupler is separated into two coupler outputs according to the rate determined by the coupling coefficient. Only an ultrasonic wave generated by a sandwich type transducer is applied to the other arm of the coupler. In this experiment, as in case of the light wave, the acoustic power is separated into both the outputs. One can observe the interaction of both the waves on the two outputs – a modulation of the light wave by means of the ultrasonic wave is possible. The output signal was detected using a PIN diode and an optical power meter (OPM). Temporary courses were observed on an oscilloscope screen. The simultaneous transmission of ultrasounds and optical radiation in optical fibers can be used in the construction of medical equipment.

Keywords: optical fiber couplers, simultaneous transmission of optical and acoustic wave in an optical fiber.

1. Introduction

Transmission of ultrasounds in optical fibers can be used in the construction of medical equipment. Since it has been demonstrated that ultrasonic waves can propagate in optical fiber (Gudra, Muc, 2007; Muc, 2009), it is now possible to use simultaneous transmissions of ultrasonic waves and laser radiation in optical fibers. Therefore it may be possible to construct laser-ultrasonic surgical knifes. As a result, it should be possible to use the advantages of an ultrasonic surgical knife in endoscopy and to use both technologies without changing the equipment during a surgical procedure. The achieving effectiveness in combining laser and ultrasonic technologies requires an appropriate mode of interaction between the light and ultrasonic energy.

The working ending of the ultrasonic surgical cutter is usually made of titanium. Long distance transmission of ultrasounds using a metal waveguide causes undesirable heating of the titanium tip and the tissue. Additionally, since the titanium tip is not elastic enough, an ultrasonic knife cannot be used in endoscopic surgery. Glass has an amorphous structure ad does not exhibit losses associated with Rayleigh scattering. An ultrasonic knife has no haemostatic properties and presents limited possibilities in cutting connective tissue. It is therefore necessary to use other cutting and coagulative equipment during a surgery. This limitation is the main disadvantage of using ultrasonic surgical knifes in endoscopic surgery, where the changing of equipment should be avoided as much as possible (Fan, Chang, 2002). Literature offers descriptions of the similarities and differences between the transmission of laser radiation and acoustic waves in optical fibers. Relations involved in acoustic wave propagation in an optical fiber have been derived. Also, because of the similarity to the widely known optical formulas, the acoustic condition related to the guiding of acoustic waves in optical fibers has been derived (Jen, 1985; 1987; Jen *et al.*, 1986; Matthews *et al.*, 1987; Muc, 2008; Nghambia *et al.*, 2001; Safaai–Jazi, 2007; Safaai–Jazi *et al.*, 1986). This paper presents a solution making it possible to put together two effects: laser radiation and vibration of the optical fiber's tip.

The Mach–Zehnder optical fiber interferometer uses optical fiber couplers to split a light beam. Methods of modulation of a light wave propagating in an optical fiber by means of ultrasonic waves, which is performed by the use of radial vibrations of piezoelectric disk and longitudinal vibrations generated by a sandwich ultrasonic transducer with a wave velocity transformer was presented in (Muc *et al.*, 2009). For use in practical systems, the acoustic fibers must be connected sometimes to sources and detectors that are spliced and coupled (Matthews *et al.*, 1987). An interferometric phase sensor with ultrasound fiber guides was proposed in (Safaai–Jazi, 2007). In literature information about simultaneous transmission of ultrasonic waves and laser radiation in optical fibers using optical fiber couplers are lacking. It is assumed that such research will allow to understand better the interaction between the two wave types. The aim of this work was, among other things, to study the way in which acoustic energy affects a laser beam.

2. Measurement system

In this work, the results of experimental studies of simultaneous transmission of ultrasonic waves and laser signals in optical fibers by means of optical fiber couplers are presented. In the system, optical fiber couplers are used to split the ultrasonic wave and the light beam. Before the main measurements were performed, the output signal amplitude representing the displacement of vibration for a sandwich type transducer with a conical and the stepped velocity transformer (called also the velocity concentrator) was measured. A capacitive sensor functioning as detector of the output ultrasonic signal was used to register the vibrations (Fig. 1).

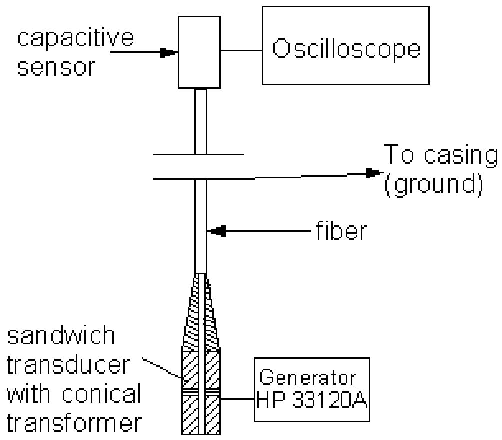

Fig. 1. A block diagram of the measurement system used to compare the achieved output signal amplitudes representing the displacement of vibration for the conical velocity concentrator.

Figure 2a shows the comparison of the output amplitudes of ultrasonic vibrations transmitted by the transducers with a stepped and a conical velocity transformer without an optical fiber using a capacitive sensor. As expected, the

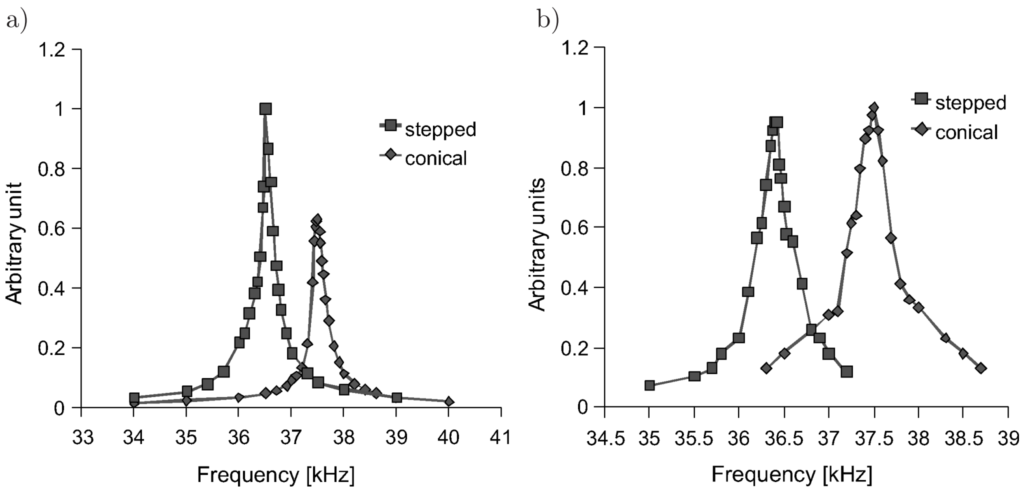

Fig. 2. Spectra of velocity concentrators: a) without an optical fiber, b) with an optical fiber.

amplitude was higher for the stepped concentrator. Figure 2b shows the results achieved with a multimode step-index optical fiber with a core diameter of 1 mm attached to the tip of the velocity concentrator. The length of the optical fiber was equal to the multiple of the length of the ultrasonic wave $\lambda/2$ (7.5 cm). This is required in order to obtain a maximum output vibration amplitude. Figure 2a shows that the stepped concentrator creates the maximum amplitude, but it is complicated to transfer energy to a fiber of small diameter. The exponential or conical concentrator is the most convenient for that purpose (Bansevičius *et al.*, 2005). The output signal amplitudes representing the displacement of the vibration were higher for the conical concentrator with an attached optical fiber. Additional experiments were performed using a power transducer with a conical velocity concentrator.

X type optical fiber couplers were used to couple the light wave with the ultrasonic wave (50/50 gradient multimode 50/125 μm and 50/50 single-mode 9/125 μm). The measurement system is shown in Fig. 3. The light wave generated by two different diodes was guided into one of the coupler's arms. First a 50/50 coupler with a single-mode telecommunications fiber was used in the process and optical power was generated by appling a diode operating at a wavelength of 1550 nm and the optical power of −11.51 dBm [0.07 mW]). Then the authors used a diode operating at a wavelength of 808 nm and the optical power −6.46 dBm (0.23 mW). A multimode gradient-index fiber was used. The optical power applied to one input is split into two outputs according to the rate determined by coupling coefficient. An ultrasonic wave (resonance frequency $f = 37.5$ kHz) generated by a sandwich type transducer was applied to the other arm of the fiber

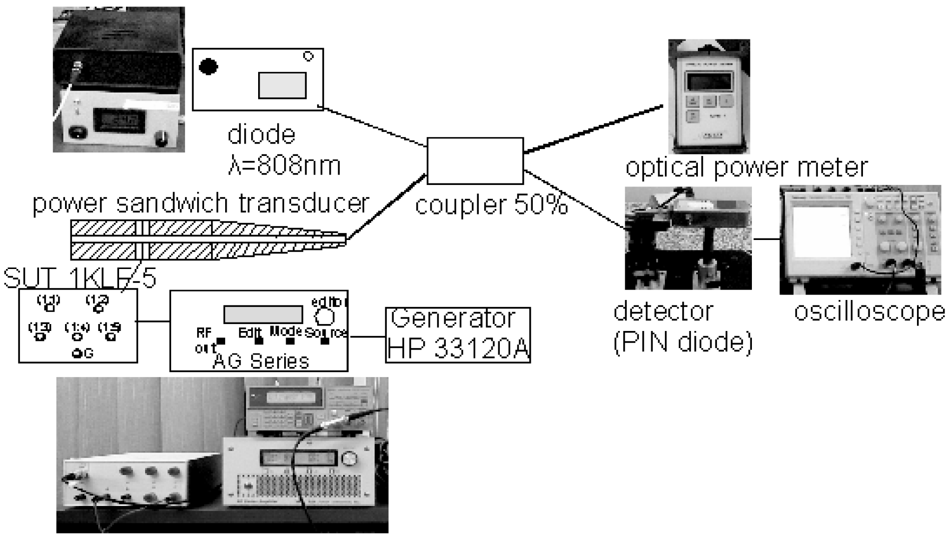

Fig. 3. A block diagram of the measurement system for simultaneous transmission of optical and acoustic waves in an optical fiber using optical fiber couplers.

coupler. An AG Series power amplifier by T&C Power Conversion with a matching transformer controlled by means of a HP 33120A generator was used too. The output signal was detected using a PIN diode and observed on an oscilloscope screen by means of an optical power meter. The input signal amplitude from the HP33120A generator was 340 mV. An ultrasonic transducer with two velocity transformers (conical and stepped) was designed and manufactured by the authors. It consists of 2 piezoelectric rings (PCM 41 made by Noliac, with outside diameter of 15.9 mm and the inside one of 7.6 mm; thickness 2.6 mm) clamped between two end metal pieces by means of a bolt. The backing of the sandwich transducer (of 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. The diameter of the end of the conical velocity transformer is 4 mm. The optical fiber is attached to the front of the end of the velocity transformer. The transducer had two resonance frequencies (f_1 = 37.5 kHz, f_2 = 55.8 kHz). 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. This was followed by additional measurements performed for the 37.5 kHz resonance frequency. Because the ultrasonic knife works at the low ultrasonic frequencies, the authors use a frequency in the range of 20–60 kHz.

3. Results of the study

The properties of sound waves propagating in an optical fiber and transmitted through an optical fiber coupler can be analogous to those of light waves propagating in an optical fiber (Jen, 1987) and a coupler. In ties experiment, as in case of light waves, the acoustic power is separated into both the outputs. One can observe the interaction of both the waves on the two outputs of the single-mode fiber coupler and the multimode fiber coupler.

The results of the measurements of coupling of the optical wave in continuous operation with the ultrasonic wave were presented.

First the continuous wave (of wavelength 1550 nm) was transmitted into the single-mode coupler.

Figure 4a represents the output signal without application of ultrasounds. Figure 4b confirms that the acoustic wave is propagating in the fiber and coupler. In Fig. 4b the output signal with the frequency of the generated ultrasonic signal (result of both the wave types being coupled) confirming the transmission of ultrasonic waves in the optical fiber coupler. A displacement, the frequency of which was equal to the activation frequency, was achieved at the end of the optical fiber. The oscilloscope screen displayed only the variable component of the signal resulting from activation with a signal of the ultrasonic frequency. The constant component of the optical signal was 320 mV. The end of the optical fiber

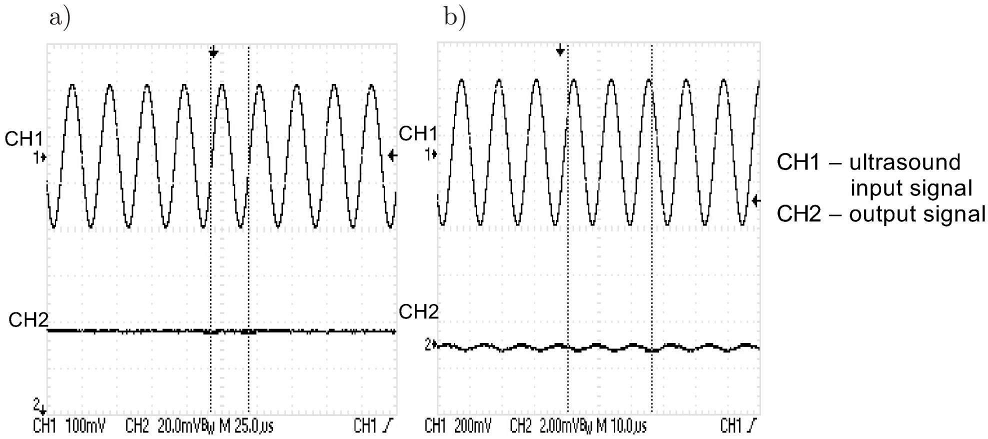

Fig. 4. Temporary courses achieved in a single-mode coupler system: a) without ultrasounds transmission, b) of transmission of coupled optical and ultrasonic waves.

vibrated and as a result the distance between it and the detector (PIN diode) increased and decreased in turns. This caused changes in the intensity of light by a value proportional to the vibration amplitude of the optical fiber, which can be observed on the oscilloscope screen presented in Figs. 7 and 8.

The measured signal of the amplitude of 0.4 mV corresponds to $P = 8$ W of the ultrasound input power. The amplitude is low, which results from the splitting the signal into two coupler inputs and the signal attenuation during transmission of the ultrasonic wave in optical fibers (Safaai–Jazi, 2007). For a single-mode optical fiber, the acoustic wave is propagating in the core and the cladding. Details of the experiments were described in (Muc, 2008). From the measurements of the optical power in relation to the applied ultrasonic power it was concluded that the ultrasonic power does not cause any change in the optical power.

Additionally, a continuous wave working at the wavelength of 808 nm was used in multimode coupler. For the multimode optical fiber the measurements returned higher output signal amplitudes, which is due to the larger diameter of the fiber in which the ultrasonic wave is propagat (Muc, 2008). The signal amplitude is 0.3 mV for the power applied to the ultrasonic transducer $P = 2$ W, and 0.8 mV for $P = 10$ W applied to the ultrasonic transducer. The oscilloscope screen, as above, displayed only the variable component of the signal resulting from activation of the system with a signal of ultrasonic frequency. The constant component of the optical signal was 428 mV. The increase in the power applied to the ultrasonic transducer results in an increase of the output signal amplitude (Fig. 5).

As a result of increasing the power of ultrasounds up to $P = 14$ W, A certain effect of modulation of the mechanical coupling was noticed (needs further study). This caused fluctuations of the coupled output signal (see Fig. 6).

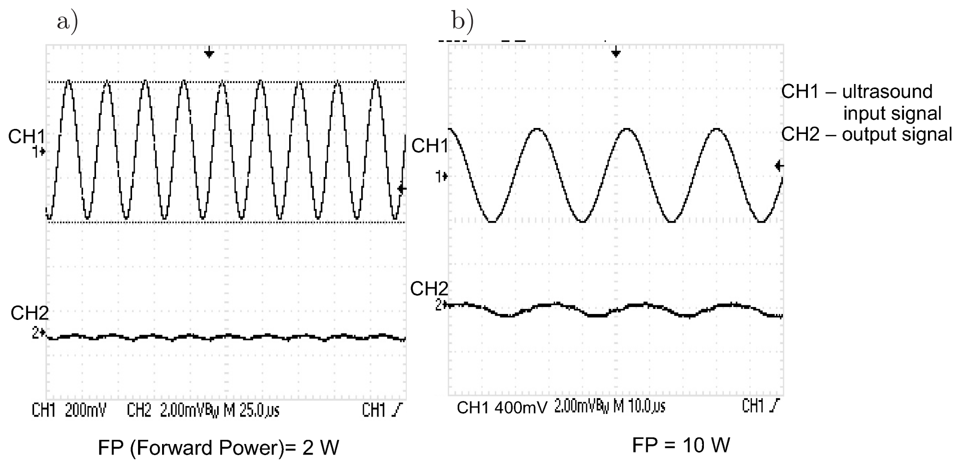

Fig. 5. Temporary courses achieved in a multi-mode coupler system when the power applied to the transducer is: a) 2 W, b) 10 W.

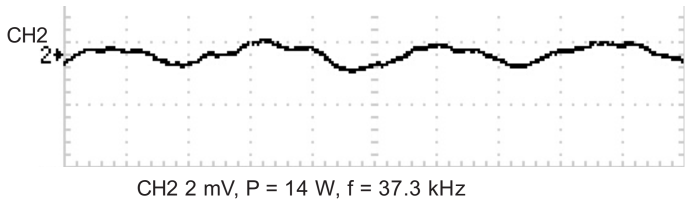

Fig. 6. Temporary courses achieved in a multi-mode coupler system when the power $P = 14$ W is applied to the transducer (the screen of the oscilloscope is shown).

Figure 7 represents the dependence of the amplitude of the output signal on the power delivered to the power sandwich ultrasonic transducer. The growth of the power applied to the transducer causes a growth of the amplitude of the output signal proportional to the displacement amplitude of the end of the multi-mode optical fiber:

- ultrasonic without coupling with the optical wave (only ultrasound),
- ultrasonic after passing through the coupler without coupling with the optical signal (without diode),
- after passing through the coupler, coupled with the optical wave; for the ultrasonic input signal $A_{\text{in}} = 0.6$ V,
- after passing through the coupler, coupled with the optical wave; for the ultrasonic input signal $A_{\text{in}} = 1$ V.

The output ultrasonic signal after passing through the coupler is smaller than the signal on the output of the power sandwich ultrasonic transducer. The 50/50 coupler was used, so the signal should be twice smaller, but it was noticed during the measurements that the output signal is not twice smaller. It is probably related to the fact that the ultrasonic signal is not being divided in the optical coupler. The coupled output signal is larger than the acoustic signal after passing

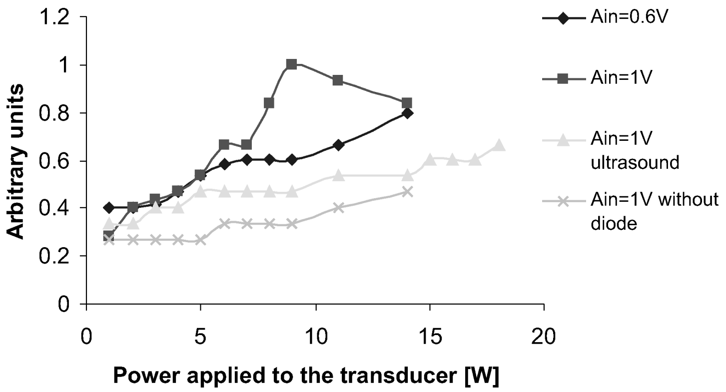

Fig. 7. The dependence of the amplitude of the coupled output signal proportional to the vibration amplitude, versus power and amplitude delivered to the power transducer when the $A_{\mathrm{in}} = 0.6$ V and $A_{\mathrm{in}} = 1$ V ultrasonic input signals are delivered; $A_{\mathrm{in}} = 1$ V only ultrasound – the ultrasonic output signal without coupler and laser diode, $A_{\mathrm{in}} = 1$ V without laser diode – the ultrasonic signal after passing through the coupler.

through the coupler. The amplitude of the coupled output signal received on the PIN detector grows together with the growth of power delivered to the power ultrasonic transducer. Additionally, the growth of the amplitude of the ultrasonic input signal ($A_{\mathrm{in}} = 0.6$ V, and $A_{\mathrm{in}} = 1$ V) causes a growth of the coupled output signal (Fig. 7).

The amplitude of the output signal is small what results from the attenuation of the ultrasonic signal during transmission of the ultrasound in optical fibers. The length of optical fibers in the applied optical couplers was 200 cm.

The growth of the power of the diode causes a growth of the amplitude of the output signal proportional to the vibration amplitude. The measured values of the output signal amplitude for both the coupler outputs are similar. This is visible in Fig. 8.

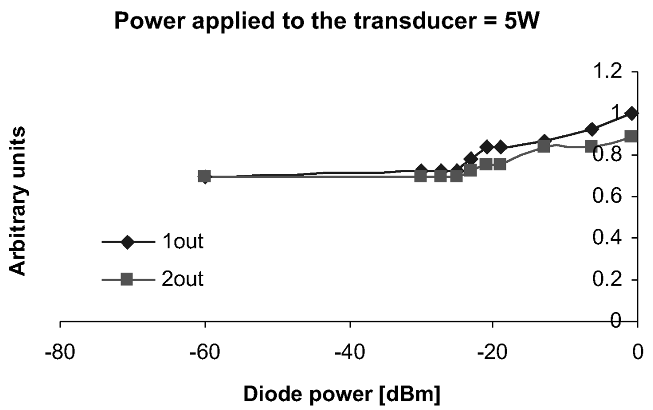

Fig. 8. Dependence of the amplitude of the output signal on the diode power, 1out – first output, 2out – second output of the coupler.

Figure 9 represents the output signal spectrum in the multimode fiber coupler. The spectrum obtained for the transducer contains the fundamental frequency (37.3 kHz) and the second harmonic (72 kHz). After transmission through the coupler a third harmonic (110 kHz) and a subharmonic (19 kHz) of the fundamental frequency are also obtained. This is clearly visible in Fig. 9 a, b, c.

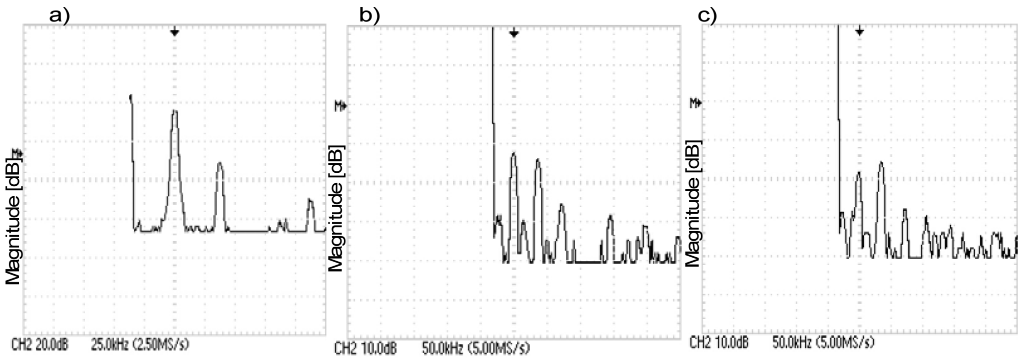

Fig. 9. Output signal spectrum: a) from a sandwich transducer, b) from a sandwich transducer after transmitting through a coupler, c) coupled optical and ultrasonic waves after transmitting through a coupler.

A change of the power of the diode (Fig. 10) does not cause changes in the output signal spectrum. A change of the power of the ultrasonic signal (Fig. 11) causes minor changes in the output signal spectrum. However, the appearance of the interference fringes results in the change of the spectrum (Fig. 12). Figure 12 shows the spectrum of coupled output signals presented in Fig. 6.

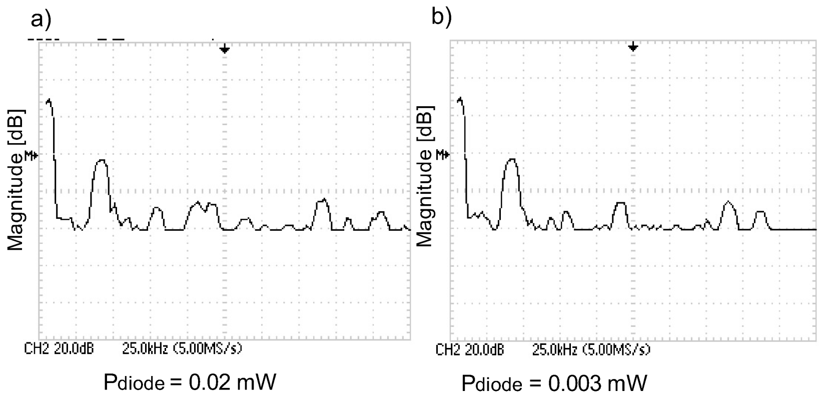

Fig. 10. The dependence of the output signal spectrum of coupled optical and ultrasonic waves after transmitting through a coupler on diode power: a) 0.02 mW and b) 0.003 mW.

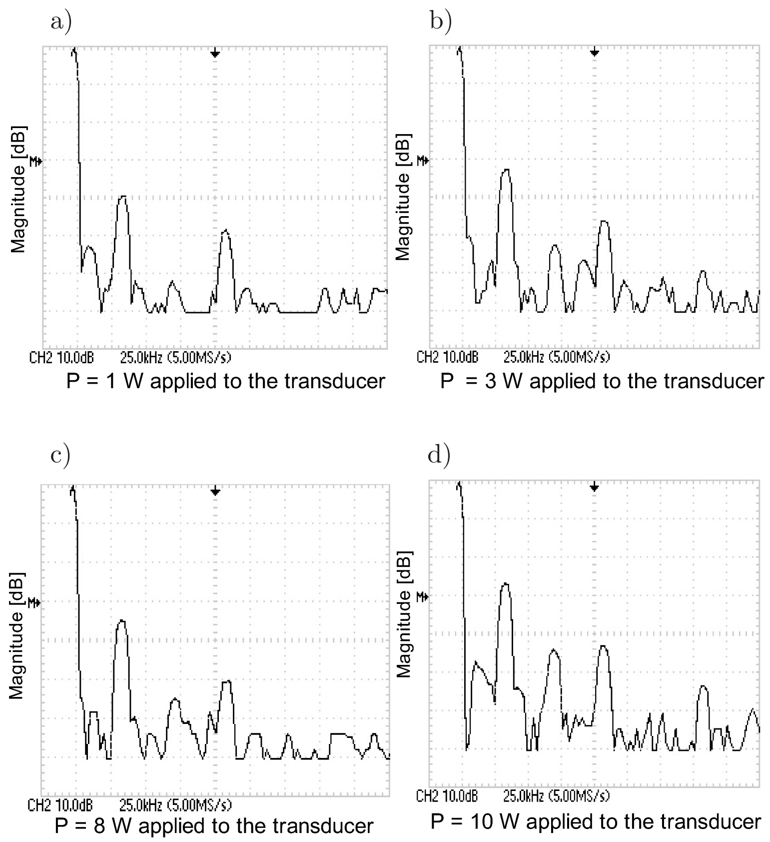

Fig. 11. The dependence of the output signal spectrum of coupled optical and ultrasonic waves after transmitting through a coupler on powers applied to the transducer: a) 1 W, b) 3 W, c) 8 W, d) 10 W.

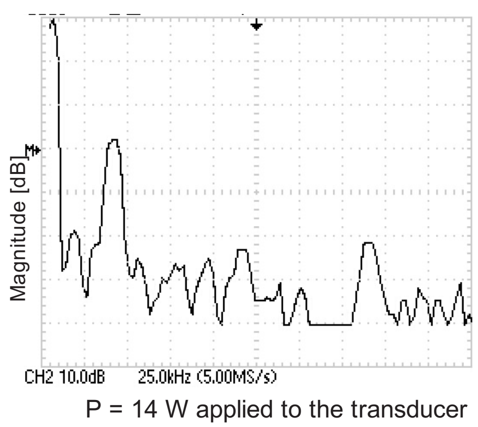

Fig. 12. Output signal spectrum achieved in a multi-mode coupler system when the power $P = 14$ W is applied to the transducer (the power for which fringers were achieved).

4. Conclusions

The possibility of coupling of optical waves in continuous operation with ultrasonic waves was approved. 50/50 X type optical fiber couplers were used to couple light waves with ultrasonic ones. Multimode gradient-index fiber couplers and single-mode step-index fiber couplers were used. The relation of the output signal amplitude from a PIN diode to the power applied to the power sandwich ultrasonic transducer was presented. A coupling of both wave types results in a change in the shape of output signal spectrum. Additionally, it should be noticed that the power used to activate the sandwich type transducer is of significant importance in relation to the interaction between the two wave types. The conclusions will be used for further analysis of the possibilities of simultaneous transmission of high power laser rays and high power ultrasonic waves in optical waveguides. The achieved results concerning the interaction of those wave types allow to assume the possibility to design a new and more efficient laser-ultrasonic surgical knife.

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