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Transmission of Ultrasonic Waves Via Optical Silica Glass Fiber Doped by 7.5% of TiO_2 with the Use of Power Sandwich Transducer

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The possibility of acoustic wave propagation in optical waveguides creates new prospects for simultaneous transmission of laser beams and ultrasonic waves. Combined laser-ultrasonic technology could be useful in e.g. surgical treatment. The article presents the results of experimental studies of transmission of ultrasonic wave in optical fibres, the core of which is doped by 7.5% of TiO_2, using a sandwich-type transducer. It also presents amplitude characteristics of an ultrasonic signal propagated in the optical fibre. Authors studied the effect which the length of the fibre has on the achieved output signal amplitudes. They presented the relation of the output signal amplitude from a capacitive sensor to the power applied to the sandwich-type transducer. The obtained results were compared with the results produced when using an optical fibre with a core doped by 3% of GeO_2, in order to select optical fibre suitable for simultaneous transmission of ultrasonic waves and laser rays.

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

1. Introduction

The best way to transmit light energy to the tissue in electromagnetic spectrum range from visible to near infrared are the optical fibres. They can transmit laser rays at distances required in medicine with little power loss (Russo, 1988). In order to select suitable light fibre for transmission of light energy, it is necessary to consider the size of the fibre and the material it is made of in the first place.

The choice of material the optical fibre is made of depends on the length of waves produced by the laser (Versadonk, Swol, 1997). In most cases, the lasers with 100% SiO_2 (quartz glass) core are used. This fibre type allows for a height power transmission. However, when using the full-contact method, the fibre could get burned as a result of thermal and chemical damage to the surface of quartz glass caused by interaction between the tissue and the optical fibre tip. That is the way which is necessary to find glass with better fatigue, thermal and chemical resistance than the quartz glass. Quartz glass doped with TiO_2 became a key material in production of the optical fibres (Hecht, 1999; Smith *et al.*, 2007). Works by Schultz and Smyth and by Evans in 1969 show that TiO_2-doped glass has coefficients of expansion 11 times lower than quartz glass; the latter is 5.5×10^{-7}/C (0–300°C) (Grant *et al.*, 1994). The coefficient of thermal expansion for quartz glass dopes by 7.5% of TiO_2 is 0.2×10^{-7} (Andreatch, McSkimin, 1976). Additionally, TiO_2 doping increases the chemical resistance, which means that the material is less affected by acid and basic solutions. In relation to that, Steve W. Martin's team developed an optical fibre that has a core made of glass doped with TiO_2 (7.5% TiO_2 and 92.5% SiO_2) and a plastic coating. Refractive index in the coating is 1.41. The core diameter used is 800 μm and thickness of the coating is 200 μm. Microscope observation revealed that both in the continuous and pulse operation modes at 15 W power and for various operation times the quartz glass got damaged, while the optical fibre with TiO_2-doped core remained intact (Grant *et al.*, 1994). Papers (Jen, 1987; Safaai–Jazi, 2007) show that it is possible to propagate acoustic waves in optical fibres. As a result combining transmission of laser beam and ultrasonic wave became a real possibility. It was shown that a fibre suitable for both types of transmission, should have the lowest core-coating normalised refractive index difference Δ_o, the lowest normalised acoustic parameter for longitudinal wave Δ_{aL} and transverse wave Δ_{aT} at the same time. Such a solution is however impossible (Gudra, Muc, 2008; Ngambia *et al.*, 2001). Fibres suitable for both types of transmission (Table 1, position 2) are a compromise between good quality in acoustic and optical applications.

Table 1. The parameters of materials used to construct optical fibres (Gudra, Muc, 2008).

No.	Optical fibre material		Optics	Acoustics	
	Core	Clading	Δ_o	Δ_{aL}	Δ_{aT}
1.	97% SiO_2, 3% GeO_2	100% SiO_2	0.0030	0.00041	0.00044
2.	92.5% SiO_2, 7.5% TiO_2	100% SiO_2	0.0170	0.00016	0.00018

The lowest normalised refractive index difference Δ_o on core-coating border can be presented as follows (Gudra, Muc, 2007):

$$\Delta_o = \frac{|n_1 - n_2|}{n_1} \ll 1, \tag{1}$$

where n_1, n_2 – refractive index in the core and coating respectively.

The lowest normalised acoustic parameter for longitudinal wave Δ_{aL} and for transversal wave Δ_{aT} can be expressed as (2) and (3) (Ngambia *et al.*, 2001; Gudra, Muc, 2007):

$$\Delta_{aL} = \frac{|v_{L1} - v_{L2}|}{v_{L1}} \ll 1, \tag{2}$$

$$\Delta_{aT} = \frac{|v_{T1} - v_{T2}|}{v_{T1}} \ll 1, \tag{3}$$

where v_{L1}, v_{L2} – longitudinal wave velocity in the core and coating respectively, v_{T1}, v_{T2} – transversal wave velocity in the core and coating respectively.

Table 1 shows that a fibre suitable for transmission of acoustic wave should have a core doped by 7.5% of TiO_2. Martin's team (Grant *et al.*, 1994) showed that the TiO_2-doped optical fibre they constructed was suitable for transmission of optical wave and can be used in surgery. Therefore, this type of optical fibre should be suitable for simultaneous laser-ultrasonic transmission.

2. Experimental study

Initially, the study related to transmission of ultrasonic wave in an optical fibre was performed using a glass fibre with a core made of SiO_2 (97%) and GeO_2 (3%) and a coating made of 100% SiO_2. Core diameter was 1 mm. The length of the optical fiber was, in approximation, a multiple of the ultrasonic wavelength (Muc, 2008; 2009).

This article shows the results of research, during which the fibre designed by Martin's team has been used. A comparison of the results obtained for an optical fibre with a core doped by 7.5% of TiO_2 and a fibre with a core doped by 3% of GeO_2, is presented in Fig. 1, which shows that the amplitudes obtained for the fiber with titanium dioxide were significantly higher despite a lower core diameter, which proves that acoustic wave is attenuated lesser by quartz glass doped with titanium dioxide. Next, output signal amplitudes were compared in relation to the frequency and the length of the optical fibre with a core doped by 7.5% of TiO_2 (Fig. 2a). Figure 2a shows that increase of the length of the fibre causes decrease of the output signal amplitude, analogous to a quartz optical fibre doped by 3% of GeO_2 (Muc, 2009). Phase shift between input and output signals for a 7.7 cm long fibre is shown in Fig. 2b.

Phase shift between input and output signals is the same as in the case of quartz optical fibre doped by 3% of GeO_2 (Muc, 2009).

Relation of the obtained output signal amplitude from a capacitive sensor to the power applied to the sandwich-type transducer was studied. This is represented in Fig. 3. Figure 4 shows a comparison of the relations of output signal amplitudes to the powers achieved for both types of optical fibres. Also in this case, higher amplitudes for the optical fibre with 7.5% of TiO_2 core doping were observed.

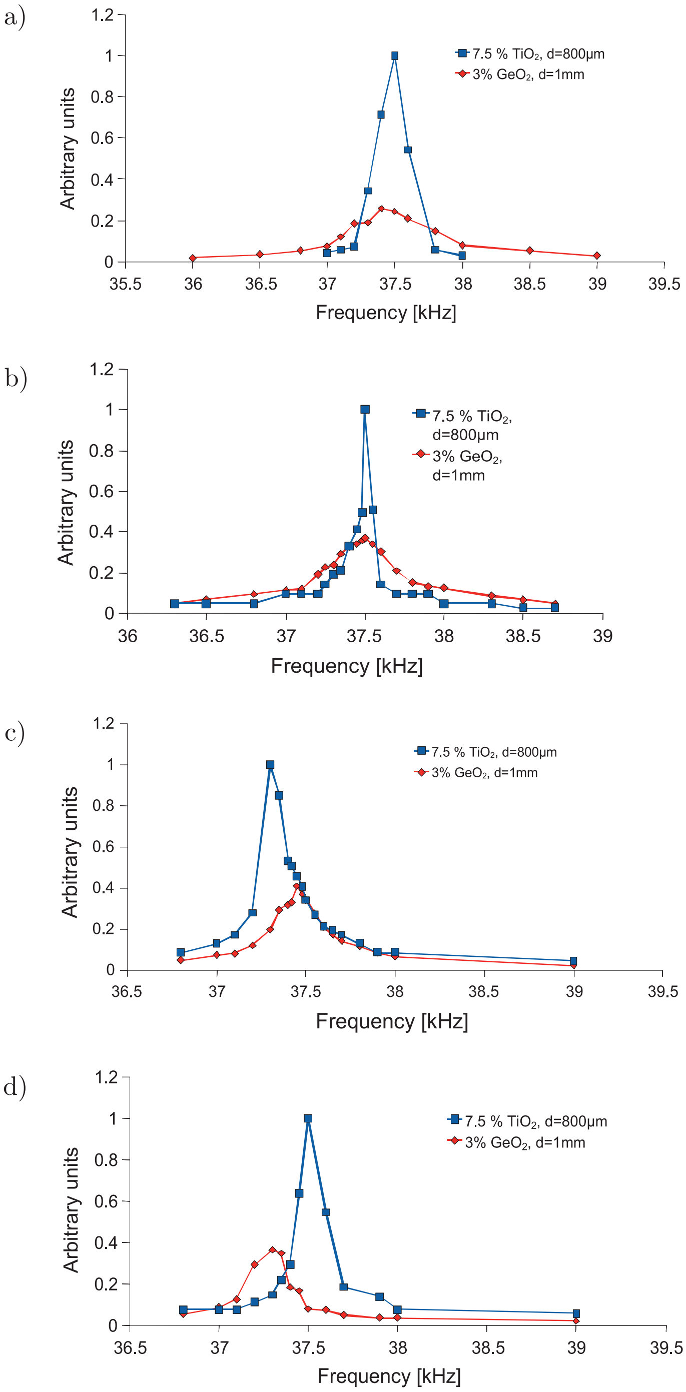


Fig. 1. Comparison of output signal amplitudes for a) 15 cm, b) 7.7 cm, c) 4.6 cm, d) 2.26 cm long optical fibres.

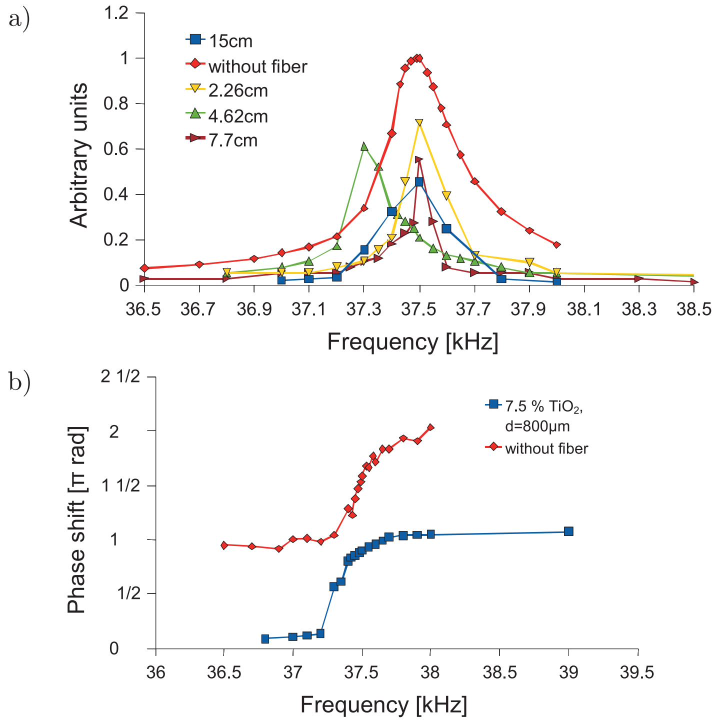
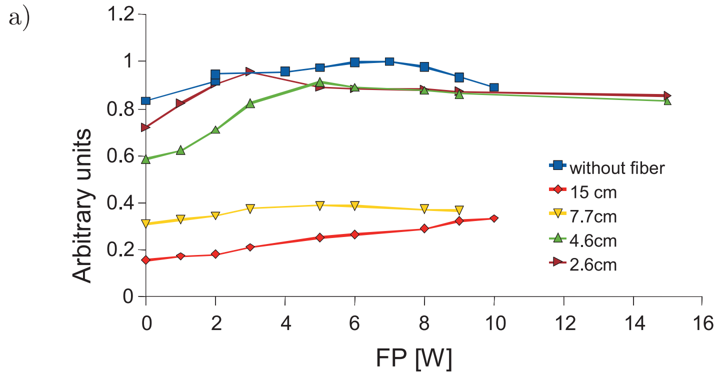


Fig. 2. Relation of output signal amplitude depending on frequency and optical fibre length (a) and phase shift between input and output signal for a 7.7 cm long fibre doped with TiO_2 (b), without fiber – when fiber is not glued to the transducer, output signal amplitude was measured at the end of the transducer.

The course of characteristics presented in Fig. 4 shows that for small powers delivered to the sandwich transducer, the output signal is increasing proportionally to this power. For larger powers, small fluctuations in the output signal can appear what results in the fact that the average amplitude does not increase.



[Fig. 3a]

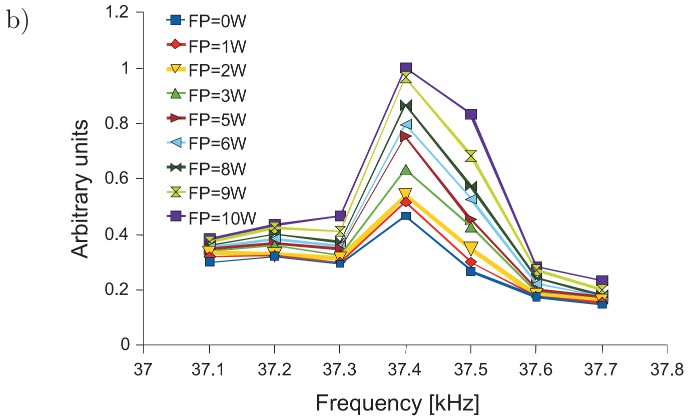


Fig. 3. Relation of output signal amplitude to: a) transducer forward power (FP), b) frequency and power for various lengths of TiO_2-doped optical fibres, without fiber – when fiber is not glued to the transducer, output signal amplitude was measured at the end of the transducer.

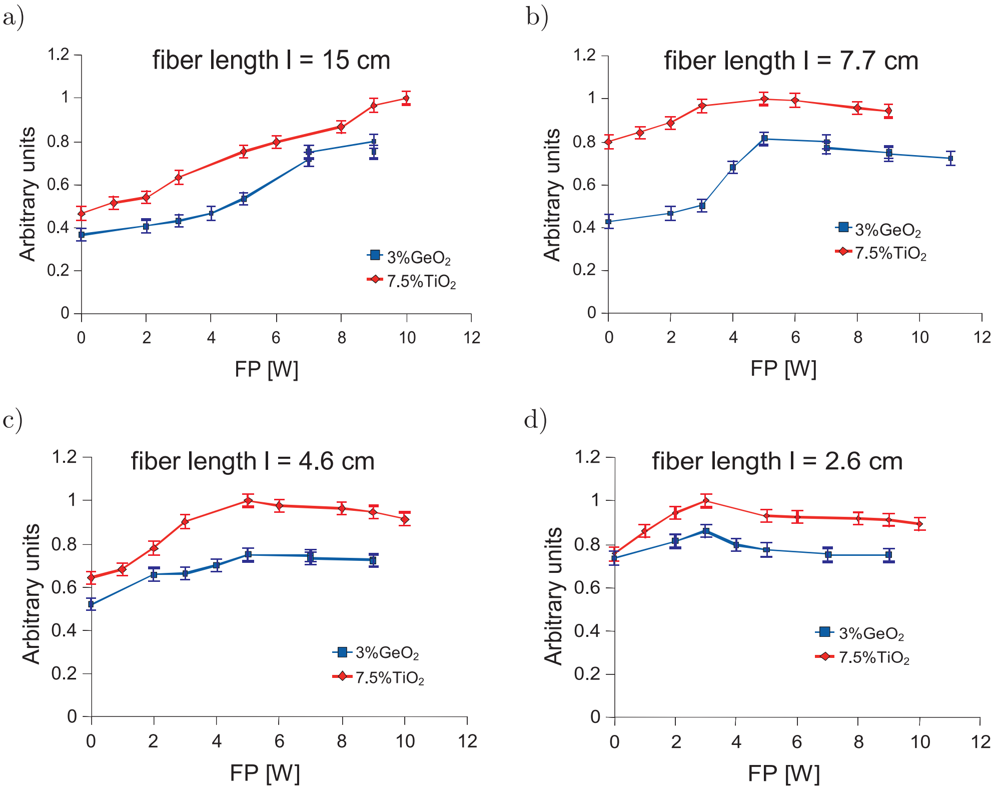
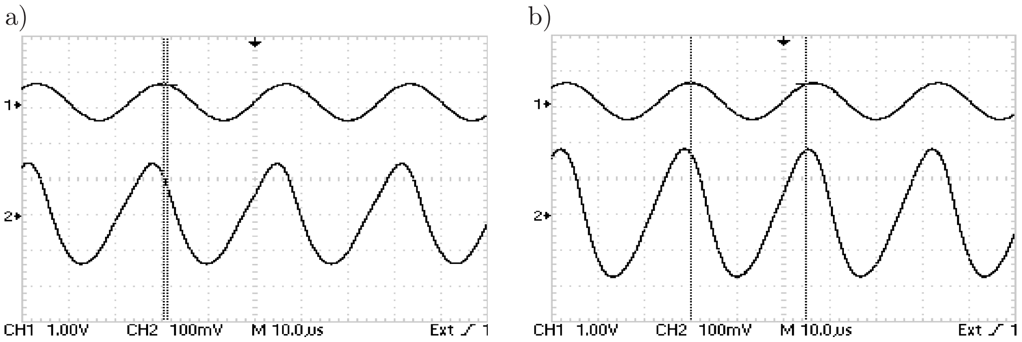
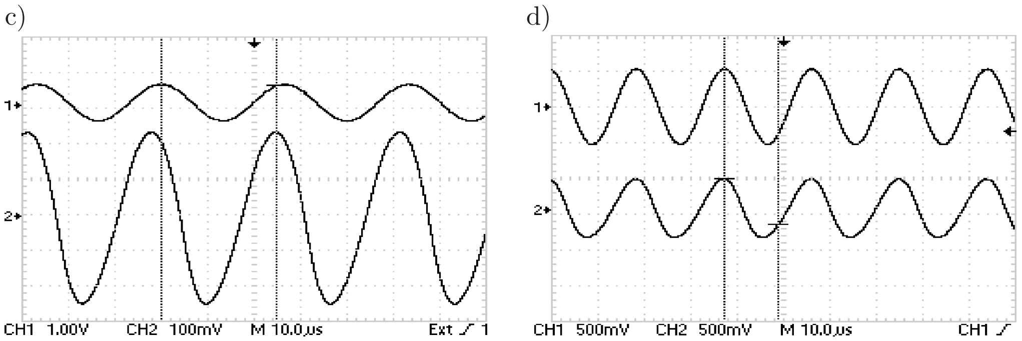


Fig. 4. Relation of output signal amplitude to forward powers FP achieved for both types of optical fibres: a) for fibre length l = 15 cm, b) for fibre length l = 7.7 cm, c) for fibre length l = 4.6 cm, d) for fibre length l = 2.6 cm.

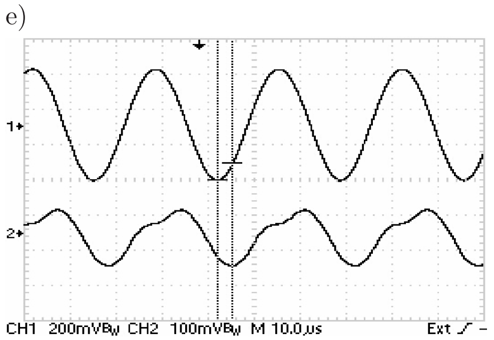
When using a titanium-doped optical fiber, no fluctuation of output signal was observed, contrary to the fibre doped by 3% of GeO_2. Temporary courses were observed on an oscilloscope screen and presented in Fig. 5.



FP = 1 W FP = 3 W



FP = 5 W FP = 14 W



l = 7.7 cm, FP = 1 W

Fig. 5. Relation of the shape of output signal to the length of the optical fibre and transducer forward power FP: a), b), c), d) for an optical fibre doped by 7.5% of TiO_2, the length of which is l = 15 cm, e) for an optical fibre with 3% of GeO_2, CH1 – input signal, CH2 – output signal.

In Fig. 6 the dependence of the output signal spectrum to the length of the optical fibre doped by 7.5% of TiO_2 was introduced. Figure 7 introduces the dependence of the output signal spectrum on the power applied to the transducer, for an optical fibre length l = 4.6 cm

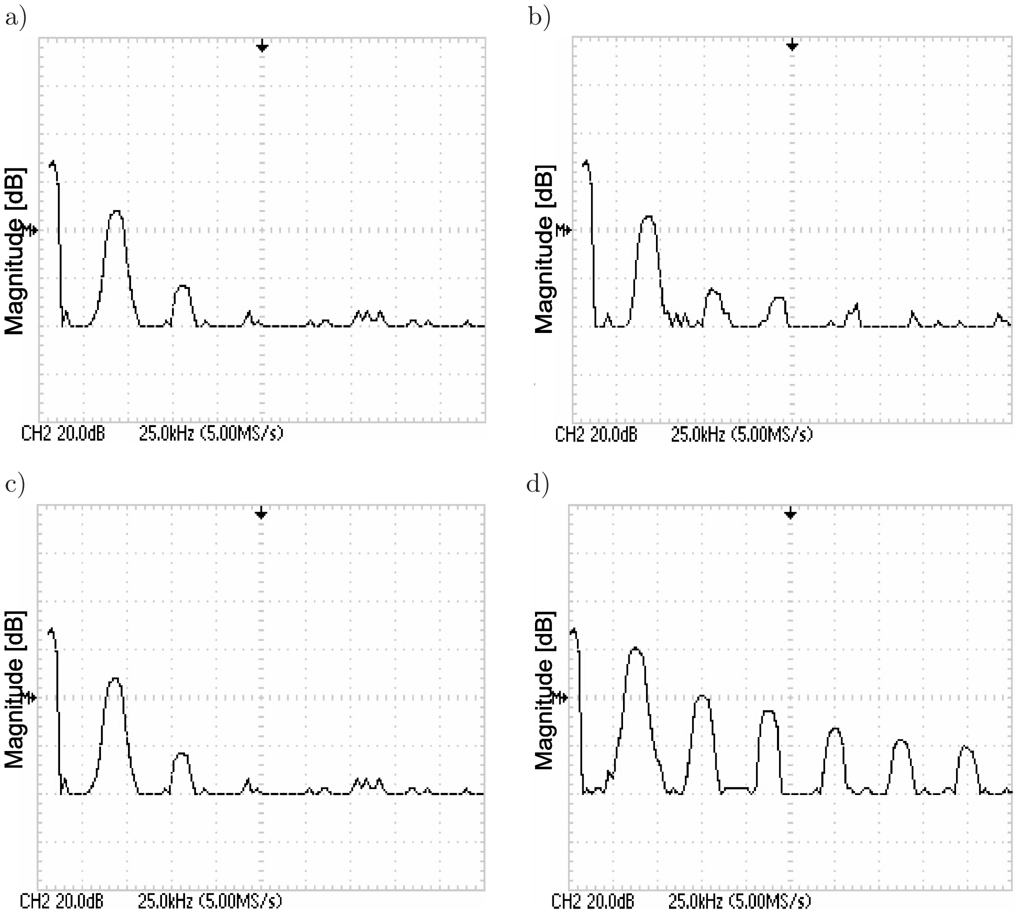
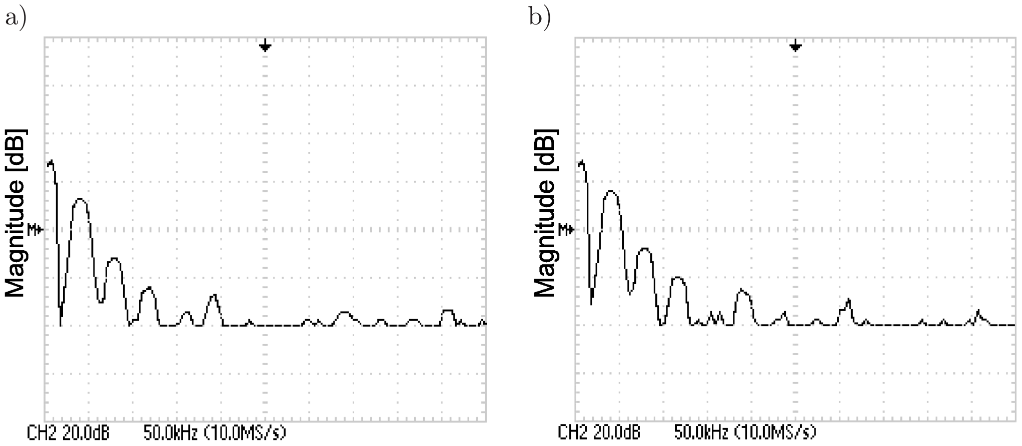


Fig. 6. The dependence of the output signal spectrum to the length of the optical fibre, doped by 7.5% of TiO_2, a) l = 2.6 cm, b) l = 4.6 cm, c) l = 7.7 cm, d) 15 cm.

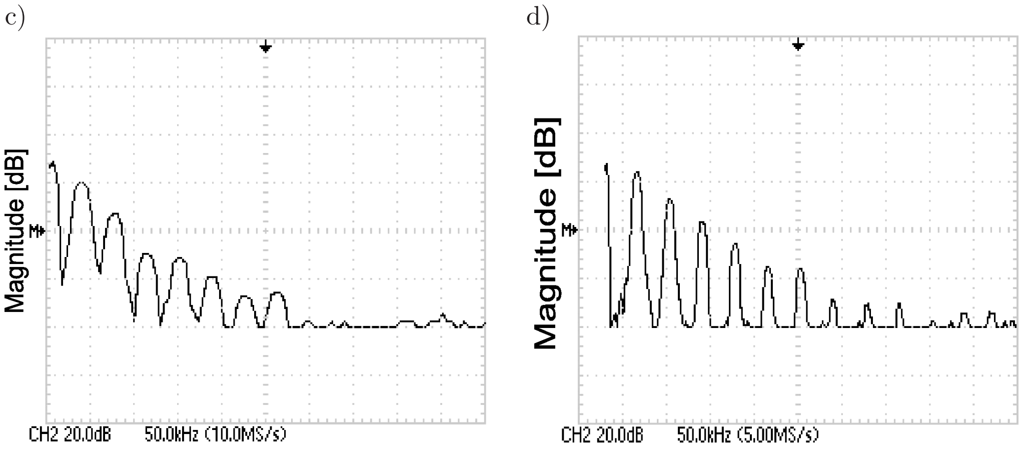
Spectra for both kinds of optical fibres with dopants of 7.5% TiO_2 and 3% of GeO_2 behave similarly. Results of fiber doped by GeO_2 were presented in (Muc, 2008; 2009). Also in this case, growth of the length of optical fibre causes the formation of harmonics in the output signal spectrum.

From Fig. 7 it follows that the spectrum of the output signal depends on the power delivered to the power sandwich-type transducer. With the growth of the power delivered to the transducer, the growth of the number of the harmonics are observed in the output signal spectrum.



FP = 4 W

FP = 6 W



FP = 12 W

l = 7.7 cm, FP = 4 W

Fig. 7. The dependence of the output signal spectrum on the power applied to the transducer, a) FP = 4 W, for an optical fibre length l = 4.6 cm doped by 7.5% of TiO_2, b) FP = 6 W, for an optical fibre length l = 4.6 cm doped by 7.5% of TiO_2, c) FP = 12 W, for an optical fibre length l = 4.6 cm doped by 7.5% of TiO_2, d) FP = 4 W for an optical fibre length l = 7.7 cm doped by 3 % of GeO_2.

3. Conclusion

The performed comparative measurements of the two types of optical fibres show that a fibre with a core doped by 7.5% of TiO_2 is better for transmission of an acoustic wave and combined laser-ultrasonic transmission than a fibre with a core doped by 3% of GeO_2. Taking into consideration that the TiO_2-doped core has better thermal and endurance parameters, the use of this type of optical fibre in a laser-ultrasonic applicator for expected applications in the process of tissue disintegration is fully justified.

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