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EXPERIMENTAL STUDY OF TRANSMISSION OF ULTRASONIC WAVE IN OPTICAL FIBERS

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Optical waveguides are commonly used to transmit electromagnetic radiation. The possibility of acoustic wave propagation in optical waveguides creates new prospects for simultaneous transmission of laser beam and ultrasonic wave.

The measurements of the transmission of ultrasound in optical waveguides were performed for three representative types of optical fiber: a multimode step refractive index, a single-mode step refractive index and a multimode graded refractive index.

Amplitude characteristics of signal propagated in optical waveguides of the three types of optical waveguides are given in this paper. The frequencies, for which amplitude maxima were obtained, overlapped resonant frequencies of a thick vibrating piezoelectric disk, which was the source of the ultrasonic waves.

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

1. Introduction

The possibility of acoustic wave propagation in optical waveguides creates new prospects for simultaneous transmission of laser beam and ultrasonic wave. Relations involved in acoustic wave propagation in a waveguide and the acoustic condition related to guiding acoustic waves in optical fibers are shown in [1, 2].

Surgery utilizes ultrasound applicator, equipped with a longitudinally vibrating ultrasonic transducer. When $C_{L1} \approx C_{L2}$ (C_{L1} – velocity of longitudinal wave in core, C_{L2} – velocity of longitudinal wave in cladding) transverse component of the mode is smaller than longitudinal component [3]. It is possible to eliminate transverse vibration mode using a suitable longitudinal wave transducer.

2. Measurement system

At the beginning of the research the possibility of transmission of ultrasounds in waveguides was checked. A system shown in Fig. 1 was constructed to make it possible.

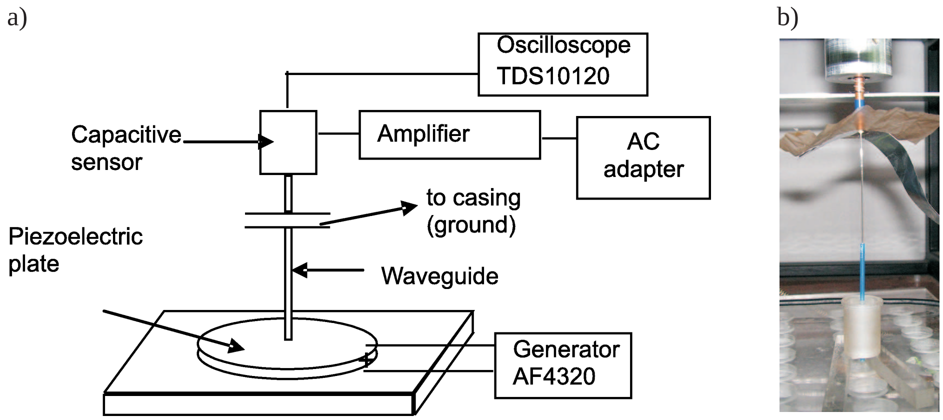

Fig. 1. Measurement system for transmission of acoustic wave in optical waveguide: a) block diagram, b) procedure of the measurements.

A optical waveguide of adequate length was attached to a thick vibrating piezoelectric plate.

The length of the waveguide should be $\lambda/2$ (or its multiple). This is required in order to obtain maximum output vibration amplitude. The length of the optical fiber was 16 cm. A capacitive sensor was used to register longitudinal vibrations.

3. Study results

To the measurements of ultrasonic wave transmission in optical waveguides, a glass optical fibers were chosen. The optical fiber's core was made of SiO_2 (97%) and GeO_2 (3%) and the cladding was 100% SiO_2. The material the optical fiber is made of enables simultaneous transmission of light and ultrasonic wave. This results from the optical and acoustic condition of the guidance of waves in optical fibres [1].

The first measurements were performed using a multi-mode optical waveguide, which was 1 mm in diameter. Piezoelectric plate has several resonance frequencies.

Ultrasonic wave transmission research were carried out introducing ultrasonic wave with frequency $f = 360$ kHz to optical fiber. Deflection of frequency compatible with the excitation frequency was obtained at the end of optical fiber what was showed in Fig. 2.

Changing the frequency of the ultrasonic wave delivered from the generator. The capacitive sensor measured the vibration frequency transmitted through optical fibre. Linear dependence was obtained (Fig. 3) which confirms ultrasonic wave transmission in optical fiber.

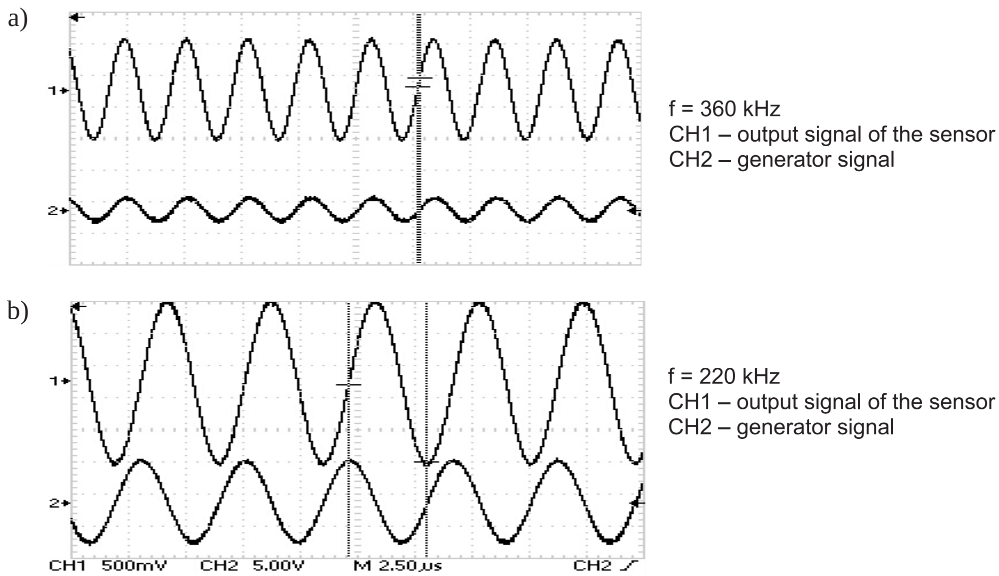

Fig. 2. Output signal amplitude: a) for frequency = 360 kHz, b) for frequency = 220 kHz.

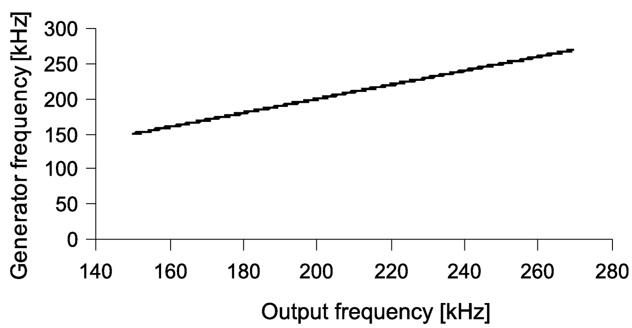

Fig. 3. Output frequency of the sensor in relation to generator frequency.

In case of multi-mode optical waveguide harmonics were obtained in addition to basic frequency. Figure 4 shows a spectrum with second and third harmonic.

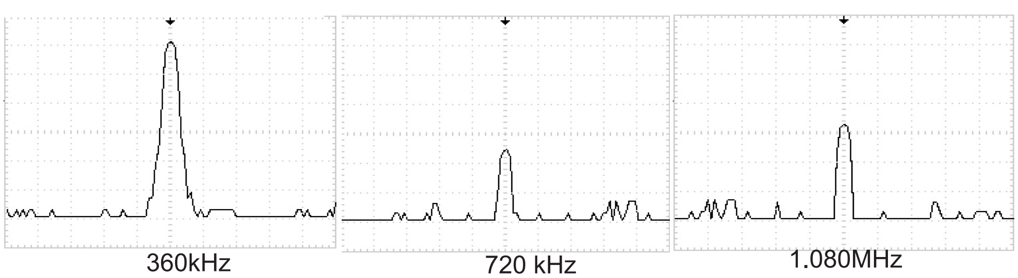

Fig. 4. Output signal spectrum for a multi-mode optical waveguide.

The voltage amplitude characteristic obtained at the capacitive sensor output for multi-mode step refractive index optical fiber (1 mm in diameter) is shown in Fig. 5a. One can notice, that the received results are reproducible.

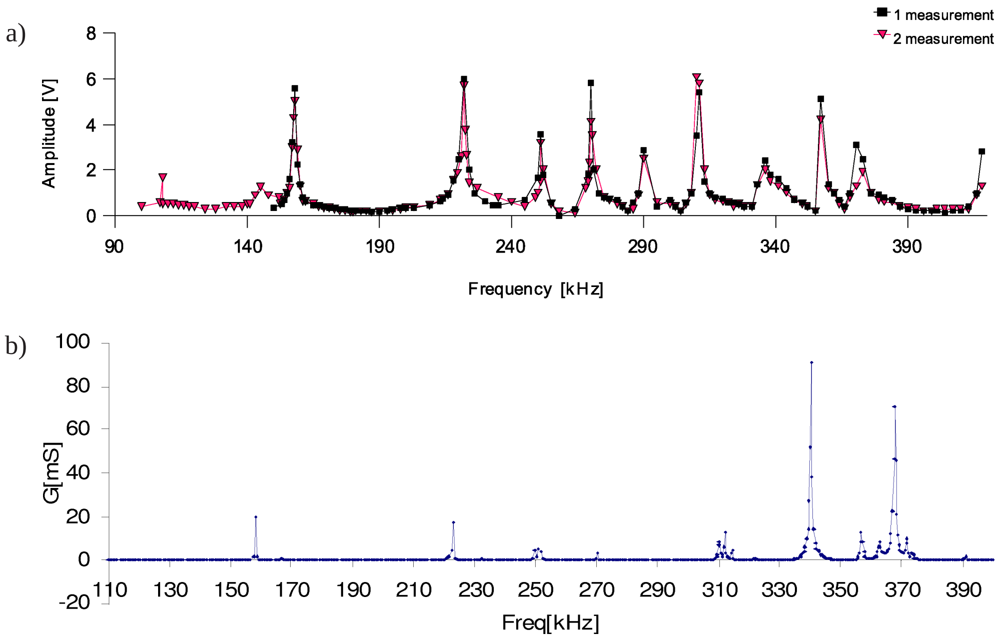

Fig. 5. Amplitude characteristic for multi-mode step refractive index optical fiber: a) at the end of the optical fiber, b) resonant frequencies of a vibrating piezoelectric disc.

The frequencies, for which deflection amplitude maxima were obtained, overlapped resonant frequencies of a vibrating piezoelectric plate (Fig. 5b).

In order to determine deflection amplitude in μm it is necessary to use a laser vibrometer. In case of an ultrasonic surgical knife amplitudes can reach 130 μm.

Further measurements were preformed for multi-mode gradient optical waveguide and a single-mode waveguide with step refraction coefficient. Cross-sections of the optical fibers used during studies are shown in Fig. 6.

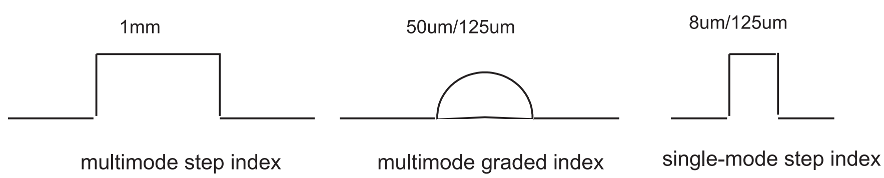

Fig. 6. Waveguides cross-section used during studies.

In Fig. 7a is showed the voltage amplitude characteristic obtained at the capacitive sensor output for multi-mode graded refractive index optical fiber. Figure 7b shows a output signal spectrum for a multi-mode graded index optical waveguide. Also in this case, harmonics were obtained in addition to basic frequency. The amplitude of the output signal was smaller than for the multi-mode step index optical fibre.

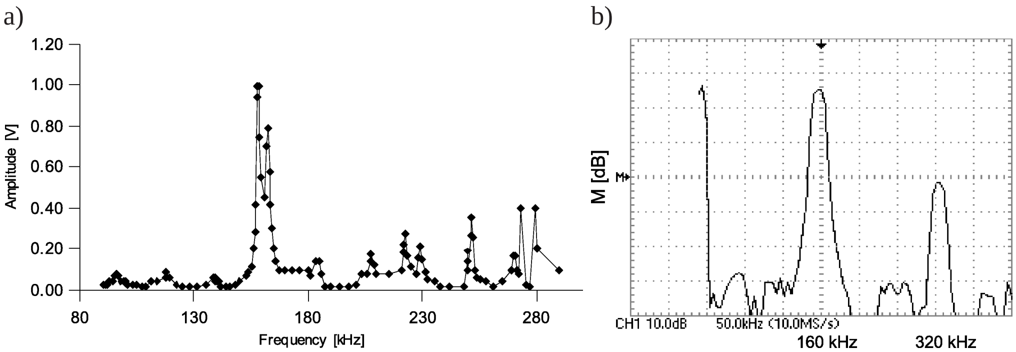

Fig. 7. Multi-mode graded refractive index optical fiber: a) amplitude characteristic, b) output signal spectrum.

The voltage amplitude characteristic obtained at the capacitive sensor output for single-mode step refractive index optical fiber is shown in Fig. 8a. Figure 8b shows a output signal spectrum. Harmonics were not observed for a single-mode waveguide.

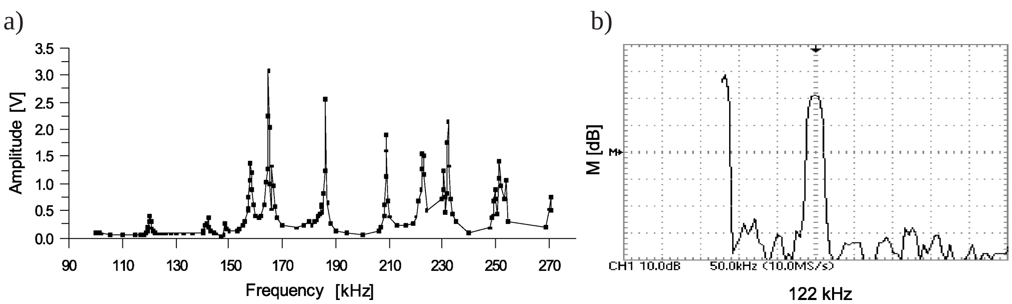

Fig. 8. Single-mode step refractive index optical fiber: a) amplitude characteristic, b) output signal spectrum.

The amplitudes of the output signal introduced in Fig. 8a are higher than in the case of multi-mode graded optical fibre and smaller than for multi-mode step index optical fibre.

Figure 9 shows the comparison of voltage amplitude characteristics measured at the capacitive sensor output for the studied waveguides. It can be observed that for a multi-mode waveguide with 1mm diameter and gradient multi-mode waveguide acoustic wave is transmitted only in the core, and in case of single-mode waveguide transmission occurs in the core and the cladding. It is evident from the voltage amplitude. The single-mode waveguide core is 8 μm in diameter and the output signal amplitude should be lower. The lowest amplitude was, however, obtained for a gradient waveguide (core diameter $= 50$ μm). Assuming that acoustic wave propagates in both core and cladding in case of single-mode waveguide (125 μm diameter), amplitude will be higher than for a gradient waveguide.

Additionally, in case of a gradient waveguide ultrasonic waves about frequencies ranging to about 300 kHz, and for single-mode optical fiber to about 250 kHz are transmitted. That is why Fig. 9b shows a limited area of comparative characteristic.

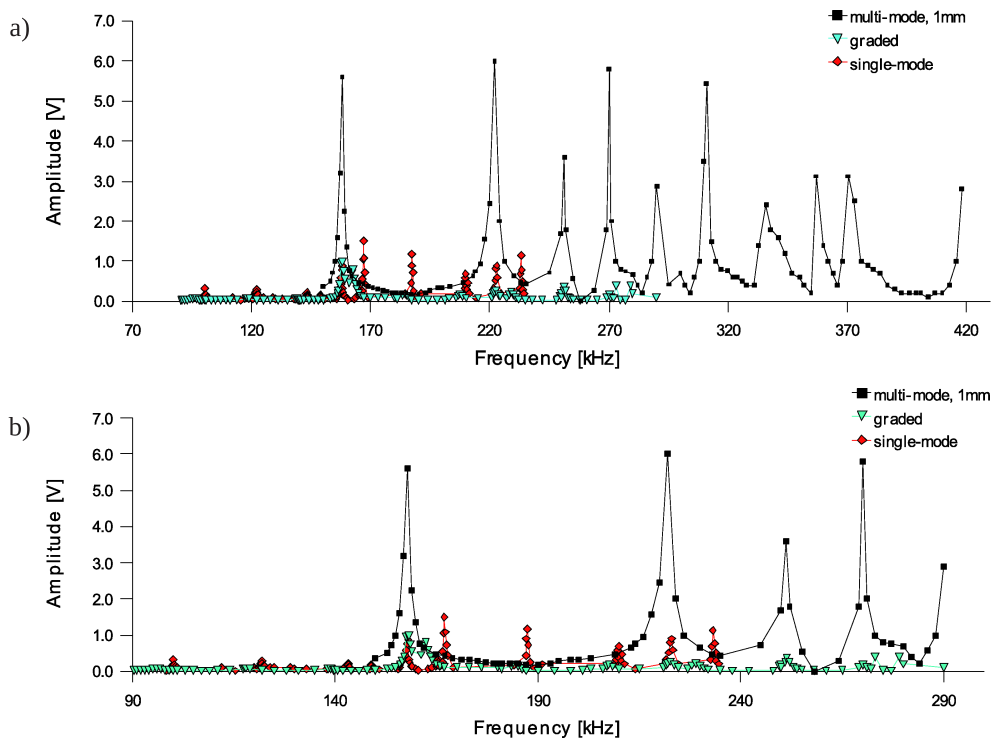

Fig. 9. Comparison of amplitude characteristics for three types of waveguides: a) full scope, b) limited frequencies area.

Figure 10 shows phase shift relation between input signal and output signal. Phase shift changes in cycles from 0 to 2π rad. In case of the studied waveguides, phase shift is similar.

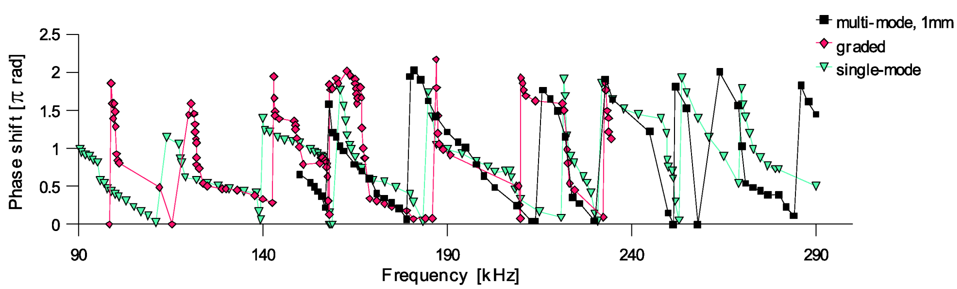

Fig. 10. Phase shift relation between input and output signal.

4. Conclusions

The paper presents the possibilities of transmission of ultrasonic wave in optical waveguides. Three representative types of waveguides were used. With the exception of a single-mode waveguide, acoustic wave propagates in the waveguide core. The larger the waveguide diameter, the easier it is to propagate low frequency acoustic wave. Conclusions will be used for further analysis of the possibilities [1] of simultaneous transmission of high power laser rays and high power ultrasonic waves in optical waveguides.

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