Subwavelength resolution in a transmission acoustic microscope configuration using fiber-tip sensors

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Subwavelength resolution in a transmission acoustic microscope configuration is demonstrated using optical fiber-tip sensors as small-sized acoustic probes. A slit with a width of 1/20 of the acoustic wavelength Λ representing the object was detected with a lateral resolution of the outer fiber diameter which was ≈1/10 Λ, and with a proper signal-to-noise ratio. Fiber preparation techniques may raise the resolution to the fiber core dimensions, and simultaneous detection of an acoustic and an optical image is proposed. © *1999 American Institute of Physics.*
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Since the successful technical implementation of the near-field scanning optical microscope (NSOM) in the 1980s, the improvement of the resolution and its extension to the subwavelength region using small detection probes have led to a wide range of new applications in microscopy. In the field of acoustics and ultrasound, ultrasonic force microscopy allows the investigation of elastic properties on the nanometer scale.[1,2] Particular applications such as the investigation of bone[3] or wood[4] require, however, only a medium resolution in the range between 1 μm and 1 mm. A conventional scanning acoustic microscope will generally be capable of meeting these requirements,[5] if frequencies between 100 MHz and 1 GHz are applied. In porous media, however, the sound absorption causes dramatic signal losses in this frequency range and the necessary reduction of the ultrasound frequency below 1 MHz limits the resolving power of the device to more than 1 mm. The investigation with an ultrasonic probe detector of subwavelength dimensions, therefore, seems to be an attractive alternative to conventional techniques.

As in the case of the NSOM, a suitable small detector or emitter is the key element of the technique. Recently, tips of optical fibers coated with optical layers have turned out to be ultrasonic sensors with a small active area and medium pressure sensitivity.[6] In this letter, subwavelength resolution in a transmission acoustic microscope configuration is presented using a fiber tip as the detection probe. A perpendicularly cut single-mode fiber was coated with a titanium layer forming an optical mirror, and the displacement of the tip due to the interaction with the sound field was measured using an interferometer. A slit representing the object with a width of about 1/20 of the acoustic wavelength could be identified with a proper signal-to-noise ratio. The spatial resolution was limited to the outer diameter of the fiber (125 μm) because of edge waves generated at the rim of the fiber. However, some possibilities are suggested that may raise the resolution to the fiber core dimensions, which are several microns in the case of single-mode devices.

The main range of application of the proposed near-field acoustic microscopy technique is the investigation of elastic properties in solids, for example, the detection of imperfections, cracks, or other local disturbances. For the first experimental test, however, a simple and variable object was needed and a slit was formed by two brass plates 0.5 mm thick (Fig. 1), which had been put on a polystyrene slab with a very thin water layer in between to ensure acoustical contact. The slab, 25 mm in diameter, represented the matrix material to be investigated. The bottom side was connected to a broadband piezoelectric transducer (0.7–3 MHz, active diameter 24 mm) via a thin water layer. The transducer was excited with tone bursts of a fixed frequency (1.4 MHz, acoustic wavelength in water $\Lambda = 1.1$ mm). The burst duration of six oscillations was chosen with respect to the length of the slab (18 mm) to separate the direct signal from rear reflections inside the slab. The acoustic field was detected with a fiber-tip sensor coupled to the object using a water drop. The sensor consisted of a single-mode fiber tip with an outer diameter of 125 μm, coated with a titanium layer 200 nm thick. The light of a laser diode ($\lambda = 674$ nm) was coupled into the fiber and reflected at the coating. Due to the acoustic interaction, the fiber front facet was moved and the resulting phase change of the reflected light was measured with a heterodyne interferometer.[7] The sensor, except for the tip, was buried in silicone which forms the top boundary of

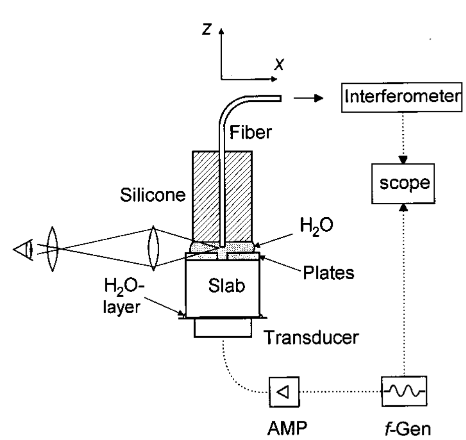

FIG. 1. Experimental setup of the transmission microscope configuration; *f*-Gen: function generator; AMP: amplifier.

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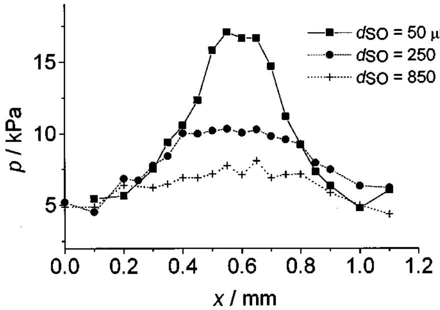

FIG. 2. Measured pressure amplitude of the sound wave transmitted through a slit 0.2 mm wide vs distance in the scanning direction dependent on the sensor–object distance d_{SO}.

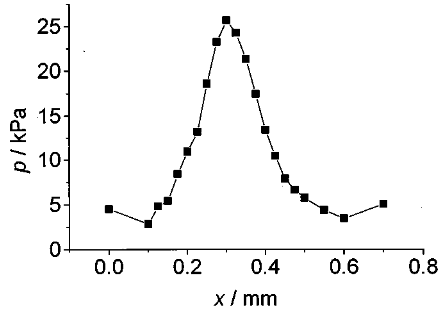

FIG. 3. Measured pressure amplitude of the sound wave transmitted through a slit 50 μm wide.

the coupling water drop. Since the acoustic impedance of the silicone was nearly matched to water, rear reflections and standing waves inside the water drop were avoided.

In this very early experiment the adjustment of the sensor and the lateral scan perpendicular to the slit were carried out by hand-driven translation stages. The distance between the sensor and the object, which is very critical with respect to the resolving power of the device,[8] was determined by a stereo microscope with a reticle in the eyepiece. By this technique an accuracy of only about 30 μm was achieved which was, however, sufficient for the first experiment. Distance regulation systems known from NSOM (Ref. 9) can be applied in a more developed version of the acoustic microscope and a significant improvement of distance accuracy is to be expected.

The heterodyne interferometer yields an output signal which is proportional to the sound pressure of the tone burst.[7] After acquiring the time-dependent interferometer output, the amplitude of the burst was determined using a fast Fourier transform, taking the scalloping losses of the Hamming window used into account.[10] The pressure amplitude obtained for the sound field transmitted through a slit 0.2 mm wide is depicted in Fig. 2 versus the scan distance *x*. The slit is well reconstructed if the distance between the sensor and the object d_{SO} is about 50 μm and the full width of half maximum (FWHM) of the pressure distribution is 310 μm. If the sensor is displaced 200 μm from the object, the resolution decreases significantly (FWHM=630 μm), although d_{SO} is still of the order of the sensor diameter and a weaker dependence of the resolution on d_{SO} was expected.[8] After further increase in the sensor distance, the contrast of the pressure distribution almost disappears (FWHM=770 μm).

The highest resolution of 310 μm in terms of the FWHM obtained during the scan of the slit 0.2 mm wide was significantly higher than the slit width. To test the resolving power of the microscope, a slit 50 μm wide, narrower than the outer fiber diameter, was investigated (Fig. 3). The FWHM of the pressure scan distribution was 160 μm in this experiment. This value is approximately equal to the sum of the object width and the outer diameter of the fiber. This leads to the assumption that edge waves generated at the outer boundary of the fiber limit the resolution. When the outer fiber edge arrives at the object slit, it acts as a source of (secondary) sound waves that propagate to the fiber center where they are detected. Part of the edge waves that would be distributed into the free half space without obstacle are reflected at the object and, thus, also contribute to the measurement signal. The smaller the distance between object and sensor the more effective is this waveguide effect. Furthermore, the sensor front face and the interface between polystyrene slab and water at the bottom of the slit form a cavity, and a weak standing wave may occur which gets out of phase when d_{SO} is changed. Therefore, edge waves, waveguide, and resonance effects seem to be the reason for both, the reduced lateral resolution and the stronger dependence of the resolution on d_{SO}.

Several possibilities can be suggested to overcome these obvious limitations of the near-field acoustic microscope technique described. If the sensor characteristic is completely known, it seems to be possible to reconstruct the true object by numerical deconvolution. Unfortunately, the determination of the complex-valued sensor transfer function turned out to be very difficult,[11] and another way using specially prepared sensor tips seems to be more promising. If the sensor tip is buried into a fused silica matrix, the outer diameter of the sensor slab can exceed the scan range and no edge will arrive in front of the object. As to the opposite alternative, the fiber tip is first tapered and then coated by the reflection layer and a small-sized sensor tip is provided.

For the heterodyne interferometer measurement, it is not necessary to have a high-reflection coating on the tip. A partly reflecting layer system allows the optical illumination of the object during the acoustic measurement. Since the dc part of the detected photocurrent then contains information about the optical reflectivity of the object while the acoustic signal is wrapped in the rf part, an optical *and* an acoustic image may be obtained at the same time. This opens up the combination of the near-field acoustic microscope proposed in this letter with a conventional scanning microscope or, in particular, with a NSOM, where tapered fiber tips are already used as favorable probes.

In conclusion, the subwavelength resolution in a transmission acoustic microscope configuration was demonstrated using a coated optical fiber tip as an acoustic probe. A slit with a width of 1/20 of the acoustic wavelength was reconstructed with a proper signal-to-noise ratio. The lateral resolution, which is limited by the outer diameter of the fiber, can be improved by preparation of special probes. Using partly reflecting layers on the fiber tip allows an acoustic and an optical image to be obtained simultaneously. The combination of the near-field acoustic microscope proposed in this letter with a conventional scanning microscope or, in particular, with a NSOM, may open up new fields of application.

[1] K. Yamanaka, MRS Bull. **21**, 36 (1996).
[2] S. Hirsekorn and W. Arnold, Ultrasonics **36**, 491 (1998).
[3] M. L. Peterson, S. Srinath, and J. Murphy, Ultrasonics **36**, 855 (1998).
[4] *Proceedings of the 10th International Symposium on Nondestructive Testing of Wood, Lausanne* edited by J. L. Sandoz (Swiss Federal Institute of Technology, 1996).
[5] A. Briggs and O. Kolosov, MRS Bull. **21**, 30 (1996).
[6] Ch. Koch, W. Molkenstruck, and R. Reibold, Ultrasound Med. Biol. **23**, 1259 (1997).
[7] Ch. Koch, Appl. Opt. **38**, 2812 (1999).
[8] E. Betzig, A. Harootunian, A. Lewis, and M. Isaacson, Appl. Opt. **25**, 1890 (1986).
[9] E. Betzig, P. L. Finn, and J. S. Weiner, Appl. Phys. Lett. **60**, 2484 (1992).
[10] F. J. Harris, Proc. IEEE **66**, 51 (1978).
[11] Ch. Koch, G. Ludwig, and W. Molkenstruck, Ultrasonics **35**, 297 (1997).