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Tuning to a particular acoustic whispering-gallery mode in the GHz range

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Abstract

Surface Acoustic Waves (SAWs) are commonly used in non-destructive testing and GHz filtering. Typical setups to study SAWs in the GHz range in the time domain make use of sub-picosecond light pulses. The absorption of pump light by the medium generates surface acoustic waves. The latter are detected by delayed probe light pulses through strain-induced variations in the optical phase. The spatiotemporal evolution of the SAWs is accessible by scanning the focusing position and time delay of the probe light pulses. In general, the laser repetition rate $f_{\text{rep}}$ (typically $\sim$80 MHz) limits such a setup to measurement frequencies that are integral multiples of $f_{\text{rep}}$. Commonly used setups focus pump light to a circular spot of a few microns in size, thus generating SAWs propagating in all directions. In the case of whispering-gallery modes (WGM) on a disk, that is, modes propagating around the disk rim, two counter-propagating modes are thereby excited with the same intensity. Here we overcome these two limitations. To access any arbitrary frequency, we modulate in intensity both the pump and the probe beams and then carry out appropriate analysis on lock-in detected probe-beam intensity variations. This opens the way to determine the acoustic dispersion curve of samples with arbitrary resonance frequencies as well as the quality factor of any chosen mode. In order to select only WGMs propagating in one direction, we make use of a spatial light modulator (SLM) programmed with the use of computer-generated holograms. In the particular case of WGMs, a windmill-shaped surface source pattern is chosen to produce acoustic WGMs with one rotation sense or the other. These new results extend the possibilities of SAW imaging by allowing fine control of excited surface acoustic modes.

Keywords: laser ultrasonics, time-resolved imaging, surface acoustic waves, whispering-gallery modes, spatial light modulator
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1 Introduction

Whispering-gallery modes (WGMs) were discovered one century ago by Lord Rayleigh in St. Paul's Cathedral (London, UK) while studying acoustics in a cylindrical geometry [1]. These modes are characterized by the localization of their energy around the rim of the cavity (i.e., around the cylindrical dome walls in St. Paul's Cathedral). Optical WGMs have similar properties in terms of the energy localization, and have been observed by spatial imaging of the optical field to sub-micron resolution [2]. More recently, spatial imaging of acoustic WGMs was achieved for sub-gigahertz surface acoustic waves (SAWs) confined on a microscopic copper disk. In those experiments, only one mode was clearly identified. This problem arises from the limitation in frequency resolution owing to the periodic pulsed laser source used for excitation and detection [3].

Surface acoustic waves have long been studied by means of time-resolved two-dimensional imaging [4-9]. Common set-ups excite and detect SAWs using an optical pump-probe technique with periodic-pulsed beams of sub-picosecond duration optical pulses to reach the GHz frequency range [7]. The pump beam is focused on the surface and generates SAWs by energy absorption and lattice expansion. The probe beam, also focused on the sample surface, detects the surface displacement originating from the generated SAWs. Two-dimensional (2D) imaging can therefore be achieved by spatially scanning the probe beam, whereas the temporal evolution of the surface displacement is accessible by use of a delay line installed on of the two beam lines. Spatiotemporal resolution of the acoustic field is therefore possible, but only at frequencies $n f_{\text{rep}}$ with $n=1, 2, 3, \ldots$ given by integer multiples of the laser repetition frequency $f_{\text{rep}}$ (typically around 80 MHz).

Recent progress in signal-processing techniques have allowed this frequency limitation to be overcome by taking advantage of sidebands introduced by an additional intensity modulation of the pump or probe beams [10-12]. In the present study, the pump-light pulse train is modulated at frequency $f_p$, and a complex amplitude representing both the in-phase and quadrature components of the out-of-plane surface velocity of the sample is extracted. The frequency spectrum corresponding to this complex signal contains sidebands at frequencies $n f_{\text{rep}} \pm f_p$ that can be separately measured. This new technique allows access to any frequency by tuning the pump frequency $f_p$.

A second limitation of previous set-ups arises from the focusing of the pump light to a circular spot. Such a spot geometry results in the generation of SAWs travelling in all directions, a situation that does not allow control of wave directionality. In the case of laser excitation and detection of whispering-gallery modes on a disk, for example, the two counter-propagating modes are both generated with similar amplitude. To overcome this second limitation, we make use of a spatial light modulator and computer-generated holograms to independently generate counter propagating modes.
2 Experience

2.1 Experimental set-up

The experimental set-up is shown in Fig. 1(a). The Ti-Sapphire laser used in the experiments has a repetition frequency $f_{\text{rep}}$ of 75.69 MHz. Part of its light is frequency doubled ($\lambda_p=415$ nm) and used for the pump beam (pulse energy $\sim 0.18$ nJ), while the other part ($\lambda_s=830$ nm) is used for the probe beam (pulse energy $\sim 0.03$ nJ). The two beams are focused on the sample surface with an objective lens at normal incidence down to a $\sim 1$ $\mu$m spot diameter. A delay line and a 2D spatial scanning system incorporating a 2-axis tilted mirror and a lens pair are mounted in the probe beam path to image the spatiotemporal evolution of the acoustic field at the sample surface at room temperature. An interferometer monitors the phase of the reflected probe light modulated by the out-of-plane sample surface motion. Associated intensity variations are captured by a photodetector connected to a lock-in amplifier. Intensity modulation of the pump beam at frequency $f_p$ ($0 < f_p \leq f_{\text{rep}}/2$) using an electro-optic modulator allows access to any SAW frequency $n f_{\text{rep}} \pm f_p$, whereas (heterodyne) intensity modulation of the probe beam at frequency $f_s$ is implemented to allow detection within the 3-MHz photodetector bandwidth (i.e., $|f_p-f_s| \leq 3$ MHz) [11].

The sample, shown in Fig. 1(b), is manufactured by International Sematech, and is similar to that used in previous experiments with limited frequency resolution [3]. It consists of a polycrystalline copper disk of radius $r_0=18.75$ $\mu$m embedded in a silicon oxide layer (thickness...
$h=370\text{nm}$) lying on a silicon nitride layer ($h=100\text{ nm}$), another silicon oxide layer ($h=550\text{ nm}$), and a Si (100) substrate. Polishing the sample to remove the excess deposited copper results in a concave disk surface [3,13]; atomic-force microscopy measurements indicate that the center of the disk is recessed with respect to the surface of the silicon oxide layer by $\sim 150\text{ nm}$.

In Fig. 1(c) one can observe the disk region through the reflected probe reflectivity 2D intensity distribution. Some damage is visible at the top of the disk. Figures 1(d) and 1(e) display two SAW images corresponding to the real part $X$ of the complex signal $Z=X+iY$ ($i^2=-1$) at 1.96 and 4.40 ns after the pump pulse arrival, respectively [3], where $X$ ($Y$) is the in-phase (quadrature) component of the measured optical phase difference. SAWs are clearly observed, and some WGMs remaining from the previous pump pulses can also be identified at the disk rim. Image acquisition of 27 frames over 0–13.1 ns takes 5 h.

2.2 Signal Analysis

Once the data for the spatiotemporal evolution of the acoustic field on the disk is acquired, we obtain the Fourier transform over the time $t$ and angle $\theta$ (in cylindrical coordinates) in order to extract the acoustic field distribution along $r$ in the frequency domain and the azimuthal order $l$, where $l>0$ corresponds to anticlockwise wave motion at each frequency:

$$F(r, l, \omega) = \frac{1}{(2\pi)^2} \int_{-\infty}^{\infty} \int_{0}^{2\pi} S(r, \theta, t)e^{-i(\omega t-l\theta)}d\theta dt,$$

where $\omega = 2\pi f$ and $S$ is the surface displacement velocity field that can be reconstructed from the complex signal $Z$ as explained in Matsuda et al. [11]. Equation (1) demonstrates that we can extract information on a WGM with an azimuthal order $l$ at a frequency $f$ as a function of the radius of the disk.

2.3 Extraction of the dispersion curves

In order to obtain the dispersion curves a series of 16 experiments were carried out, varying the pump frequency. For each pump frequency, we obtain results at the frequencies associated with the lower sideband (at $nf_{\text{rep}}-fp$) and with the upper sideband (at $nf_{\text{rep}}+fp$). A first set of 3 experiments with pump frequencies $f_p=6.30, 18.91$ and $31.51\text{ MHz}$ were done to obtain data at a frequency step of $\sim 12.6\text{ MHz}$. Then 13 experiments were done with a smaller frequency step ($0.7\leq f_p\leq 14.3$) to follow the evolution of a particular mode with the aim of extracting its associated quality factor $Q$. For each experiment, we acquire data at a 27 frequencies, leading to a total of 432 studied frequencies between 0 and 1 GHz.

For each frequency we obtain the results for each mode $l$, and determine whether a WGM is involved or not. A mode $l$ is considered to be excited and detected when the following conditions are fulfilled:

i) positive and the negative azimuthal order (for a given $|l|$) show the same maximum;
Fig. 2: (a) Dispersion curves for positive azimuthal order. Red crosses indicate experimentally extracted WGMs. The solid curve is an interpolation, and blue circles indicate the position of individual modes lying on this curve. (b) Normalized amplitude ratio versus frequency for the azimuthal mode \( l=26 \). Horizontal dashed lines represent \( 1/\sqrt{2} \) of the maximum amplitude for positive and negative azimuthal orders.

ii) the ratio of the average amplitude at the disk rim to that at in the inner region for the mode \( l \), denoted by \( R_l \), should be greater than 20.

With these two conditions, we detect several tens of frequencies for which a WGM is identified. They are presented in Fig. 2(a). They clearly follow a single dispersion curves (except for a few modes that, after looking at their associated displacements, are shown to correspond to second order modes). The dispersion curve can be fitted to a second-order polynomial function which can then be discretised to fit integer values for the azimuthal orders.

Finally, several modes are detected for close frequencies, such as mode 26 at the frequencies 750±5 MHz. By plotting the normalized amplitude of the ratio \( R_l \) defined above, one can follow a curve resonance and extract the associated quality factor. Figure 2.(b) displays the resonance curves of the modes \( l=\pm 26 \). The \( Q \) factor can be estimated from the \( 1/\sqrt{2} \) bandwidth, and it reads \( Q_{l=26}=450 \) and \( Q_{l=-26}=350 \). Other quality factors can be similarly obtained for modes 18, 27, 31 or 41, for example, and all show \( Q \approx 400 \) or less. In all these cases, the positive and negative azimuthal order data exhibit similar amplitudes, where the slight differences are attributed to imperfections of the disk and especially to the damage region near the top of the disk (see Fig. 1c).

2.4 Control of the propagation direction

In the previous set of experiments, the pump light was focused to a circular spot of a few microns in size, which therefore generates SAWs propagating in all directions. In the particular
case of WGMs, the two counter-propagating modes are excited with the same intensity (e.g., see Fig. 2(b)). This symmetry can be a limitation in the case of filtering applications or for the detection of defects. To overcome this limitation, we present a method for acoustic wave imaging with arbitrary acoustic source shapes provided by the use of a spatial light modulator (SLM) and computer-generated holograms. The holograms are calculated by a direct-search algorithm [15]. Arbitrary acoustic source shapes can be realized, and, to illustrate this, we propose here the use of an annular-shaped source covering half a circle in order to control the acoustic wave propagation direction.

In order to excite WGMs and control the energy propagation, we program the SLM to generate the required half-circle pump source spot on the sample in order to focus the SAWs at the centre of the annulus. When the annulus is oriented to focus SAWs in the downward direction (Fig. 3(b)) on right-hand side of the disk rim, one can expect that excited WGMs with a counter-clockwise propagation (i.e., with a positive azimuthal order) will be generated with a higher amplitude than in the opposite sense. The reverse situation should be expected when the annulus is oriented to focus upwards on the same position on the disk rim (Fig. 3(d)).

An experiment has been done on a similar sample (but a different disk in order to avoid the damage at its top) with both these excitation methods, and with a pump frequency set at \( f_p = 1 \) MHz. For these two experiments the analysis proceeds similarly in order to extract the excited WGMs and differentiate the positive azimuthal orders from the negative ones. Results are displayed in Figs. 3(a) and 3(c), respectively. One can see that the symmetry between the

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\begin{align*}
&l=17 - 528 \text{ MHz} && l=22 - 680 \text{ MHz} \\
&(a) \quad l>0 \quad l>0 \\
&(b) \quad l>0 \quad l>0 \\
&(c) \quad l<0 \quad l<0 \\
&(d) \quad l<0 \quad l<0
\end{align*}
\]

Fig. 3:(a)-(c) Evolution of the normalized amplitude of the modes \( l=17 \) at 528 MHz (a) and \( l=22 \) at 680 MHz (b) as a function of the radius for the WGM associated with a positive (negative) azimuthal order, corresponding to an anti-clockwise (clockwise) propagation propagation. (b)-(d): Insets: shape (in blue) of the acoustic source generated with the spatial light modulator and expected senses of acoustic energy flow (in green).
positive and negative azimuthal-order intensities is now broken. In Fig. 3(a) (3(c)), one can also see that the WGMs with positive (negative) azimuthal order have an amplitude 2.5 times higher than those with negative (positive). This confirms the possibility of controlling the orientation of the excited WGMs.

3 Conclusions

In conclusion, we have demonstrated arbitrary-frequency ultrafast control and imaging of a micro-acoustic system with an optical time-resolved technique. By the use of modulated heterodyne pump-probe spectroscopic method, we have isolated and imaged a wide range of GHz surface-acoustic whispering-gallery modes in a microscopic copper disk. Radial modes of first and second order are catalogued and imaged, and selected resonances probed with ∼1 MHz frequency resolution. Corresponding $Q$ factors are extracted for both clockwise and anticlockwise propagation. Secondly, the use of a spatial light modulator allows control of the propagation direction of the whispering-gallery modes. Our approach should apply to other forms of acoustic whispering gallery modes. Promising further applications include the investigation of the modes and bands of phononic crystals, acoustic metamaterials, and commercially important SAW devices for telecommunications.

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5 References


