Brillouin microscopy on microwave-induced phonons in LiNbO$_3$

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Abstract. High-performance Brillouin microscopy is proposed as a powerful technique to characterize the lobe of microwave-induced acoustic phonons generated by interdigital finger electrodes in a LiNbO$_3$ device. The generation efficiency is compared with the intensity of thermal phonons of the same wave vector and polarization.

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1. Introduction

There exists a tremendously growing demand for high speed and large flux but safe data transfer systems. This means that signals have to be transferred at high frequencies and large bandwidth. Actual interest is therefore focused on the GHz regime.
The latter demands are accompanied by the requirement of miniaturization of the data transfer systems. The conversion of electromagnetic signals to acoustic ones and vice versa is one of the major solutions to this problem. The so-called surface acoustic wave (SAW) devices yield the technical realization of this conversion problem. In these devices, SAWs are excited preferentially at GHz frequencies by interdigital electrode (IDE) structures on piezoelectric substrates [1, 2].

It is worth noting that there is a great interest in the field distribution of such surface waves and usually accompanying bulk acoustic waves. To optimize the electromagnetic → acoustic → electromagnetic conversion, it is important to get as much information as possible about the redistribution of the injected electromagnetic energy into the generated acoustic field and vice versa.

To visualize the spatial acoustic field distribution in SAW devices many experiments have been performed, but we will mention only a few: optical interferometry [3], atomic force microscopy [4], x-ray spectroscopy [5] and scanning electron microscopy [6]. It is evident that methods that measure acoustic properties directly would be the most efficient ones and that holds especially true for the GHz range.

Brillouin spectroscopy (BS) is an optical spectroscopy which is predominantly used to investigate hypersonic properties based on the thermally excited acoustic phonons [7]–[9]. However, in principle, it is also possible to use BS as a probe for coherently excited phonon and magnon modes (see e.g. [10]–[16]) provided the laws of conservation of momentum and energy hold within the scattering process. An excellent review about the different possibilities for the excitation of high-frequency phonons, especially of the optical detection of coherently excited microwave surface phonons, was given by Stegeman [17]. Fabry– Pérot techniques are amongst the most suitable ones cited in [17]. However, as has been shown in the literature [14], the detection of coherently excited hypersonic waves by BS seriously suffers from the difficulty of adjusting the scattering geometry in such a way that the law of momentum conservation is exactly fulfilled [14]. It has been shown previously [18] that the so-called RIΘA-scattering geometry provides a fast and efficient method to change continuously the magnitude of a phonon wave vector of a given direction.

Another shortcoming of the BS was until recently the very limited spatial resolution of this method. In this paper, we will show that the µ-Brillouin spectroscopy (µ-BS) in combination with the RIΘA scattering geometry will overcome this problem [19]. In addition, we will demonstrate that by using IDEs on piezoelectric LiNbO₃, we can detect bulk acoustic waves accompanying surface modes and characterize their spatial distribution. The spatial resolution of about 1 µm of our new µ-BS technique enables us to determine the ‘near’ acoustic field residing immediately below the IDE structure. A first attempt will be made to characterize the coil of the acoustic antenna given by the IDE structure.

2. Results and discussion

To study microwave induced phonons by µ-BS, we used a commercial (Y + 41°) cut (X, Y and Z are the crystallographic axes according to IRE-standards) of LiNbO₃. The plate-like sample with orthorhombic shape is optically polished. The z-axis of the rectangular sample coordinate system has been chosen to be orthogonal to the plate surface and collinear to the (Y + 41°) axis. The thickness is Δz = 300 µm. The crystallographic X-axis has been chosen to be directed along
the \( x \)-axis of the crystal plate having a length of \( \Delta x = 20 \text{ mm} \). The width of the crystal plate is \( \Delta y = 15 \text{ mm} \). Figure 1(a) shows a schematic representation of the IDE structure (Al) deposited by sputtering on one of the two polished surfaces of the LiNbO\(_3\) crystal plate. The IDEs are connected by gold wires to suitable microwave connectors. The gold wires are Wetch-bonded to the IDEs. The IDE array has standard dimensions to generate SAWs of 584 MHz. The spatial period of the interdigital is \( 8 \mu\text{m} \) and the total surface of the array is about \( 1 \times 1 \text{ mm}^2 \). As a consequence, the IDE array is ill-conditioned for the generation of SAWs with frequencies of some GHz. The microwave generator is electrically decoupled from the sample by a broadband isolator. It turns out that the electromagnetic impedance matching at a driving frequency of 4 GHz is rather satisfactory. Using a 3 dB coupler and a microwave power meter the standing wave ratio (SWR) was measured to be 2.15. To perform BS using the so-called RI\( \Theta \)A-scattering geometry [18], we have deposited, in addition to the IDEs, aluminium mirrors (M, figure 1(a)) on the same surface but adjacent to the IDEs. The mirrors M are, however, electrically isolated from the IDE array.

Figure 1(b) schematically shows the situation of the electric field in the crystal underneath the Al electrodes. In the new coordinate system \( E_\| \) and \( E_\perp \) (with \( E_\| \equiv E_x \) and \( E_\perp \equiv E_y \)), the wave propagating along the \( \| \) axis is created via the piezoelectric constant \( d_{15} = 13 \text{ pm V}^{-1} \) and the wave propagating along normally to the surface is created via the piezoelectric constants \( d_{31} = 16 \text{ pm V}^{-1} \) and \( d_{33} = 35 \text{ pm V}^{-1} \).
Figure 2. Schematic representation of the RI$\Theta$A scattering geometry. N$_1$, N$_2$, rotation axes; M, mirror; L$_1$, L$_2$, lenses; P, prism; IB, incoming laser beam; $k^{\Theta A}_i$, wave vector of the exciting laser beam; $k^{\Theta A}_s$, wave vector of the scattered light; $q^{\Theta A}$, phonon wave vector; $\Theta$, scattering angle. See the text for further explanations.

The $\mu$-BS measurements were performed with a high-performance Tandem–Fabry–Pérot [20] using the RI$\Theta$A-scattering geometry [18]. The $\mu$-BS technique has been widely discussed in [18]. This microscopic technique differs from that of $\mu$-Raman spectrometers insofar that we are able to realize a wide range of scattering angles. The $\mu$-Brillouin spectrometer consists mainly of a Tandem–Fabry–Pérot and an optical pre-amplifier having an optical amplification of about 140. We thus amplify the illuminated volume but detect only a tiny part of it. Using a suitable goniometer to position the scattering volume within the sample, we are able to scan the mechanical properties throughout the sample. Thus, the high spatial resolution of our $\mu$-BS technique is at the expense of the spectral intensity of the phonon modes. Fortunately, because of the significant microwave amplification of the phonons, spectral intensity is not a problem for the experiments performed on microwave-induced phonons.

Figure 2 shows a possibility for realizing the RI$\Theta$A scattering using an external back-scattering arrangement. To carry out the RI$\Theta$A scattering, the sample is fixed on an optical reflecting support M. In the present case, M are the Al films deposited on the LiNbO$_3$ sample close to the IDE structure (figure 1(a)). The laser beam IB is sent via a prism P to the sample S. The beam IB is reflected at the mirror M, creating a laser beam with wave vector $k^{\Theta A}_i$. Taking into account that the scattering volume is positioned close to M, the scattered light of wave vector $k^{\Theta A}_s$ emerges from the reflected incident beam (along $k^{\Theta A}_i$) and is sent in the direction of the spectrometer SB. As shown in figure 2, the angle $\Theta$ defines the outer scattering angle for the RI$\Theta$A-scattering geometry. The sagittal angle $\Theta/2$ can be continuously changed between 0$^\circ$ and almost 90$^\circ$ by rotating the sample around the axis N$_2$ (figure 2), which lies in the interface between the reflecting surface M and the sample surface S. It is obvious that a wide range of
wave vectors can be realized simply by rotating the sample around \(N_2\) but keeping the optical set-up fixed: rotating the sample around \(N_2\) only changes the magnitude of \(q^{\Theta A}\) but fortunately not its direction. For our \(\mu\)-BS measurements on microwave-induced phonons, it is of extreme importance that the scattering volume is located close to the piezoelectrically excited surface \(M\), on the one hand, and that the unit vector \(q^{\Theta A}/|q^{\Theta A}|\) is invariant under the change of the sagittal angle \(\Theta\) and essentially lies in the film plane on the other.

Using Snellius’ law, it can easily be shown that the acoustic wavelength \(\Lambda^{\Theta A}\) almost does not depend on the optical refraction properties of the crystalline sample, yielding approximately [21]:

\[
\frac{q^{\Theta A}}{\Lambda^{\Theta A}} = \frac{4\pi}{\lambda_0} \sin \left( \frac{\Theta}{2} \right),
\]

where \(\lambda_0 = 532\) nm is the vacuum wavelength of the laser. Consequently, the resulting sound velocity is also independent of the refractive index,

\[
\frac{v^{\Theta A}}{\Lambda^{\Theta A}} = \frac{f^{\Theta A,\lambda_0}}{2 \sin \Theta / 2}.
\]

Of course, \(v^{\Theta A}\) is not invariant under rotation around \(N_1\) but probes the crystal symmetry in the plane of the crystal plate [18, 20]. Taking into account that the acoustic attenuation in a crystal increases with the square of the sound frequency involved, it is desirable to probe the existence of microwave-induced phonons first, at low frequencies. Unfortunately, close to ‘forward scattering’, laser light enters the Brillouin spectrometer and saturates the photomultiplier and thus limits the range of scattering angles. An experimental compromise was found for an outer scattering angle of \(\Theta = 14^\circ\), yielding an acoustic wavelength of \(\Lambda = 2.2\) \(\mu\)m. The scattering was chosen to detect phonon propagation along the crystallographic \(X\)-direction.

Figure 3 (circle dots) shows a typical Brillouin spectrum as measured by light scattering on thermal phonons propagating along the \(x\)-axis. The scattering volume was positioned at point \(A\) (figure 1(a)), which is about 2.5 mm at the right of the centre of the IDE array. The abscissa of the spectrum plot is calibrated in GHz, the ordinate gives the scattering intensity. The spectral lines of the quasi-longitudinal and the quasi-transverse phonon modes are well resolved. Further spectral components could not be resolved. The related phonon frequencies are \(f_{QL} = 3.9\) GHz and \(f_{QT} = 2.5\) GHz. Since we have not determined the spectrometer profile, we cannot give absolute temporal attenuation coefficients (see below).

Knowing \(f_{QL}\), we then switched on the microwave generator just at this frequency. The microwave power coupled with the IDE array amounts to \(P_{MW}(f_{QL}) = 41\) mW. Taking into account that the IDE array not only induces hypersonic waves in the LiNbO\(_3\) device but also acts as a microwave antenna, it is expected that a large fraction of \(P_{MW}\) is irradiated. Figure 3 (square symbols) shows a typical Brillouin spectrum measured on the mirror \(M\) of the microwave-driven device.

As a matter of fact, the anti-Stokes line reinforced by the microwave excitation is strongly amplified: while the peak intensity of the Stokes line is about 100 counts the peak intensity of the anti-Stokes line amounts to \(33 \times 10^3\) counts. Moreover, the line-widths (full-width half-maximum, FWHM) is as small as 90 MHz. It is worth noting that if we place the scattering volume to the left of the IDE array instead of amplifying the anti-Stokes line, the Stokes line is
amplified. It is interesting to note that, taking into account the spectral width of the microwave signal of some kHz, the spectral profile of the amplified spectral component (anti-Stokes line in figure 3, square dots) is indicative for the transmission profile of the Brillouin spectrometer.

A question arises about the hypersound field generated immediately underneath the IDE array at our test frequency of 3.9 GHz. Using the $\mu$-BS technique, we were able to place the scattering volume on a central electrode finger of the IDE array. As a result, figure 4 shows that both the Stokes and the anti-Stokes line are amplified to the same amount. This result is expected since the left- and the right-running acoustic waves are generated simultaneously underneath the IDE array. As can be seen from figure 4 some unexpected phonon lines are detected at $\pm 1.6, 2.4$ and $3.1$ GHz. These additional peaks are of course the result of an inelastic scattering process, which is observed only if the scattering volume is located on the finger structure. Taking into account that the scattering wave vector $k^{SA}_{\theta}$ is fixed, it is probable that the additional scattering process is due to a ‘splitting’ of the incoming laser light within the sample. We believe that the splitting occurs on the interdigital fingers structure. Probably, the focalized incoming laser beam hits metallic finger partially which are adjacent to the central one. The parasitic reflection of laser light from these adjacent finger structures yields additional light beams in the direction, which deviates from the main reflected laser beam. Probably, these additional weak light beams with varying wave vectors $k_i$ cause the observed additional phonon lines. If this hypothesis is true, then these additional phonon wave vectors are no longer coplanar to the sample surface. Additional experiments have to be made to verify these arguments.

To get some insight into the generation mechanism of the microwave-induced acoustic bulk waves, we have tested the relation between the power of the applied microwave signal and the integral intensity of the amplified phonon line in the Brillouin spectrum. According to figure 5,
Figure 4. Brillouin scattering with microwave excitation; $P_{MW} = 41\,\text{mW}$, $f_{MW} = 3.9\,\text{GHz}$. The scattering volume position is indicated by location B in figure 1(a).

Figure 5. Brillouin scattering response of the measured induced phonons as a function of the applied microwave power, $f_{MW} = 3.9\,\text{GHz}$ (+, experimental data; —, linear regression line).
the intensity response is a linear function of the applied power, at least for the applied range of microwave power.

\(\mu\)-BS offers the possibility to characterize the spatial distribution of the microwave-induced acoustic field. For this purpose, we have measured Brillouin spectra along two different trajectories positioned at different distances from the generating IDE array. Figure 6 shows the related results. Each data point within figure 6 corresponds to the integrated intensity of an induced phonon at the given location within the sample. It turns out that the acoustic emission lobe of the IDE array is rather narrow and opens only a little with distance from the generating IDE array.

3. Conclusion

\(\mu\)-BS was used to measure microwave-induced acoustic bulk waves in LiNbO\(_3\) which accompany the generation of SAWs. \(\mu\)-BS is an especially versatile method to detect even extremely weak acoustic signals. Moreover, this new technique is able to characterize the intensity profile of the acoustic field within the whole sample. As a matter of fact, we were even able to measure the acoustic excitation in the immediate vicinity of the electrodes of the transducer.

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