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# Characterization of surface acoustic waves by stroboscopic white-light interferometry

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**Abstract:** We present phase-sensitive absolute amplitude measurements of surface acoustic wave fields obtained using a stroboscopic white-light interferometer. The data analysis makes use of the high resolution available in the measured interferometric phase data, enabling the characterization of the out-of-plane surface vibration fields in electrically excited microstructures with better than 100 pm amplitude resolution. The setup uses a supercontinuum light source with tailored spectral properties for obtaining the high amplitude resolution. The duration of the light pulses is less than 300 ps to allow the detection of high frequencies. These capabilities enabled a detailed measurement of the focusing of surface acoustic waves by an annular interdigital transducer structure operating at 74 MHz, featuring a maximum vibration amplitude of 3 nm.

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**OCIS codes:** (320.6629) Supercontinuum generation; (110.3175) Interferometric imaging; (180.3170) Interference microscopy; (240.6690) Surface waves.

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## 1. Introduction

Non-contact optical probing techniques are widely utilized to directly measure surface vibration fields in a wide variety of electromechanical devices [1–5]. Scanning laser interferometry [6–9], capable of detecting (sub)picometer vibration amplitudes, has dominated the characterization of high-frequency electromechanical devices, for which the typical maximum amplitudes are below 1 nm and the operation frequencies can extend up to several GHz. The widespread use of silicon-based MEMS resonators with their typical operation frequencies ranging from sub-kHz to several tens of MHz and with their maximum out-of-plane vibration amplitudes of even up to several micrometers has raised an interest in utilizing stroboscopic white-light interferometry (SWLI) for device characterization [10–12]. The SWLI technique is particularly interesting as it readily enables unambiguous detection of vibrations with amplitudes greater than the fringe period of the interferometric signal. Stroboscopic imaging requires short enough light pulses, so that the vibrational motion can be effectively "frozen" by synchronizing the illumination pulses to the excitation of the device, thus enabling the use of static optical profiling techniques. Periodic vibrational motion can be characterized by repeating the measurement for different phase delays between the sample driving and the light pulses.

Even though the strongest vibrations in MEMS components may have rather large amplitudes, often weak effects such as spurious resonances or energy leakage from a resonator are of particular interest. Additionally, other types of electromechanical devices, such as those based on surface acoustic waves (SAW) and bulk acoustic waves (BAW) feature not only small maximum vibration amplitudes of the order of nm, but also have their operation frequencies range from several tens of MHz up to several GHz. Therefore, a sub-nm detection limit combined with a large dynamic range is needed to provide an in-depth characterization of surface vibrations in such devices.

The performance of the SWLI setups, however, has typically been limited to the characterization of low-frequency (up to a few MHz) and high-amplitude (even several  $\mu\text{m}$ ) vibrations. The use of the SWLI technique for the characterization of high-frequency electromechanical devices requires a stable, low-noise, light source with proper spectral characteristics, short enough light pulses and freely adjustable pulse repetition rate. Furthermore, the source has to be synchronized to the excitation of the sample with a low pulse jitter. To achieve the required amplitude detection limit, the SWLI system has to be mechanically stable in order to eliminate temporal drift and environmental fluctuations during a measurement. Additionally, high

enough light power and low enough camera noise are essential together with advanced data analysis methods.

It has been shown that, by combining the fringe envelope location measurement with phase detection of the interferometric signal, a sub-100 pm amplitude limit can be obtained in a SWLI setup using a LED light source with 8 ns optical pulses [13]. Achieving significantly shorter pulses with high enough power from a LED source is technically challenging. To facilitate measurements of high-frequency electromechanical components we have developed a super-continuum (SC) based light source with favorable spectral characteristics and optical pulse width (FWHM) of less than 300 ps. The SWLI system combined with this light source allows us to achieve the previously reported sub-100 pm amplitude limit [14].

In this paper, the SC based SWLI setup has been used to measure the focusing of surface acoustic waves at 74 MHz by an annular interdigital transducer (AIDT) structure. The SWLI setup together with enhanced data-analysis are capable of measuring the phase and absolute-amplitude of the surface vibration fields with a minimum detectable amplitude of less than 100 pm. This provides sufficient dynamic range for the measurement even though the maximum vibration amplitudes are as small as 3 nm. These results push the applicability of SWLI to new limits in the measurement of surface vibrations: The technique is no longer limited to MEMS structures, which are typically low-frequency devices with relatively high vibration amplitudes, but it is now demonstrated to be applicable to the characterization of SAW devices as well. The performance obtained is already comparable to that of full-field laser interferometry [15].

## 2. Stroboscopic white-light interferometer and data analysis

We have recently designed and built a SC source [14] which provides both optimized spectral properties in the visible and a freely adjustable repetition rate of the short optical pulses thus enabling SWLI applications over a wide frequency range. The SC light source design is schematically presented in Fig. 1. A gain-switched laser diode (PICOPOWER-LD-1064-FC-SF-50, ALPHALAS GmbH) emits shorter than 50 ps optical pulses that are amplified in a two-stage fiber amplifier to kW peak powers. Part of the output at 1064 nm is frequency doubled in a KTP crystal, and the resulting optical pulses at 1064 nm and 532 nm are used in a dual-wavelength pumping scheme [16] to generate an SC spectrum in a microstructured optical fiber (MOF) at low pump powers. The pump laser is controlled with an external trigger to generate optical pulses at freely selectable repetition rates ranging from a single shot up to 50 MHz with a pulse timing jitter specified to be less than 6 ps.

The SC light source is used in our Michelson-type white-light interferometer setup [13] as illustrated in Fig. 1. The SC output is spectrally filtered with a 40 nm (FWHM) bandpass filter (BPF) centered at 500 nm in order to optimize the spectral characteristics for high-resolution SWLI (an averaged pulse spectrum is provided in Fig. 1(a)). The filtered light is coupled and guided through a 2 m long multimode (MM) optical fiber, which serves to reduce speckle noise and to eliminate spatial dependence of the spectral characteristics of the light before the interferometer. The resulting illumination pulses were measured to be shorter than 310 ps (FWHM) in a measurement that was limited by the rise and fall times (both specified to be less than 200 ps) of the photodetector (Newport Model 877), see Fig. 1(b). The result is in agreement with an estimated temporal pulse width of less than 200 ps for the light source. For a detailed description of the light source and the interferometer, see Refs. [13, 14].

The filtered SC pulses are split by a non-polarizing beam splitter cube into a reference and a sample arm of the Michelson-type interferometer setup. The two beams are reflected back

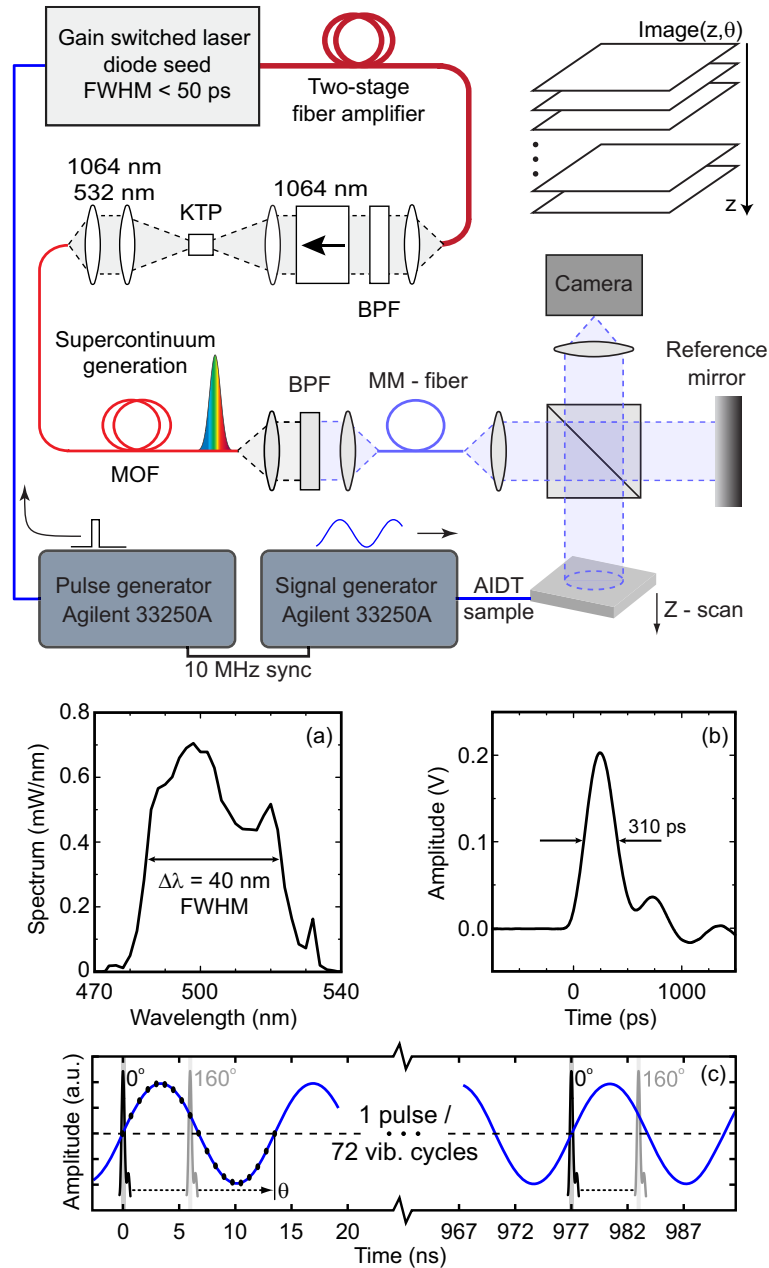


Fig. 1. Schematic presentation of the Michelson-type SWLI setup utilizing a supercontinuum source. (a) Measured averaged illumination pulse spectrum. (b) Measured temporal width of the illumination pulse. (c) Illustration of optical pulses synchronized to the electrical excitation of the sample. The sample is periodically illuminated at the 72nd subharmonic frequency of the vibration. The relative phase,  $\theta$ , between the two signals is controlled to acquire the instantaneous surface deflection at a number of phase values indicated on the sine wave by black dots (pulses at  $0^\circ$  and  $160^\circ$  provided for illustration).

from the sample and a reference mirror, and are recombined by the beam splitter for imaging of the resulting interference pattern on a digital camera (Point Grey BFLY-PGE-09S2M-CS). The sample position is scanned along the optical z-axis by a piezoelectric translator stage to vary the optical path length difference between the two arms of the SWLI.

To measure surface vibration fields, the phase  $\theta$  between the excitation of the sample and the illumination pulses is varied in 20 degree steps over the vibration cycle at each z-position, such that a set of instantaneous deformation data can be obtained by high-resolution frequency-domain white-light interferometer data-analysis techniques [13]. To obtain the desired amplitude and phase data of the sinusoidal surface vibration, the set of measured instantaneous deformations is analyzed by utilizing Fourier transform techniques. When the phase values span exactly one period of the surface vibration, the vibration amplitude and phase are obtained from the first bin of the discrete Fourier transform while the surface topography can be obtained from the zeroth bin [13].

### 3. Sample and measurement results

The key advantage of a laser-based illumination source for SWLI over LED-based sources is the capability to produce short optical pulses with desired spectral characteristics. Currently the highest-frequency vibration modes that have been characterized with LED-based setups have been around 14 MHz [13]. In that case, the optical pulse duration was limited to 8 ns resulting already in an illumination ratio of 11 percent. With our SC based setup, we are now able to measure the vibration fields in a 74 MHz SAW device, which requires both high amplitude-resolution and short optical pulses. Assuming the measured upper limit of 310 ps for the optical pulse duration of our source results in an illumination ratio of approximately 2 percent. In this case, the specified pulse jitter (6 ps) of the laser source remains insignificant. Since the maximum repetition rate of our SC source (50 MHz) is below the frequency of interest, the frequency generators driving the sample and the light source are synchronized such that the SC source is operated at around 1 MHz, at the 72nd sub-harmonic of the 73.728 MHz vibration frequency of the sample (for an illustration, see Fig. 1(c)). The relatively low pulse repetition rate is used to minimize potential heat-induced drifts of the SC-source and to lower the average optical power incident on the sample.

The SAW device features an annular interdigital transducer structure (see Fig. 2(a)), designed to focus the SAWs on the piezoelectric material to a single, diffraction-limited spot that shows a large concentration of acoustic energy. This concept is thought to be of practical significance in the design of new intense microacoustic sources that can be used for instance for enhanced acousto-optical interactions [17]. To achieve effective focusing of SAWs on a piezoelectric substrate, the shape of the metalized transducing fingers follows the wave surface, thereby deviating from a circular shape to account for the anisotropic nature of the wave propagation. At the frequency of 73.728 MHz of the vibration mode, the average SAW wavelength is approximately 50  $\mu\text{m}$ . The sample is driven with a 3.95  $V_{p-p}$  excitation and the absolute-amplitude and phase data extracted from the measurement are presented in Figs. 2(c) and 2(d). The amplitude and phase data can be combined to reconstruct a 3D view of the instantaneous surface deformation at any phase of the vibration, enabling also the visualization of the wave behavior as an animation. The instantaneous surface deformation corresponding to the maximum deflection at the focal spot is depicted in Fig. 2(b). The resonant vibration mode at 73.728 MHz results in a standing wave pattern with the waves converging to a diffraction limited focal spot in the center of the device. The concentration of the energy at the focal spot results in a large amplitude of up to 3 nm, whereas the wave amplitude decays quickly when moving away from the center. Since the device features a standing wave pattern, we can infer the detection limit in the measurement to be less than 100 pm by inspecting the nodal lines,

a result that is in line with the previously reported system performance [13, 14]. Furthermore, the SWLI results compare well with those previously obtained from the same structure by two different scanning heterodyne laser interferometers [17, 18].

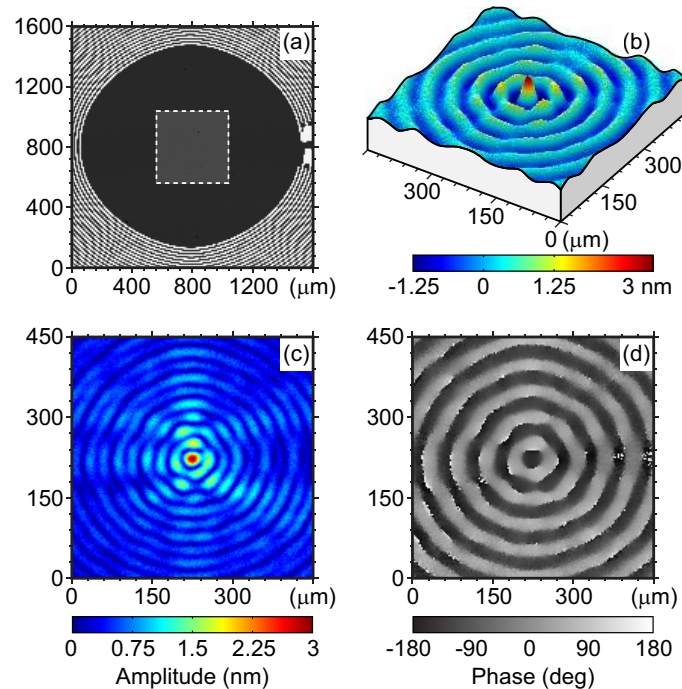


Fig. 2. (a) Microscope image of the AIDT intended to excite SAWs to form an intense focal spot. The measurement area within the AIDT is denoted by gray shading and a dashed border line. (b) 3D view of the instantaneous surface vibration obtained by combining the amplitude and phase information. Amplitude (c) and phase (d) fields of the surface vibration, obtained from the SWLI measurement data.

#### 4. Conclusions

We have utilized a supercontinuum based SWLI setup to characterize surface acoustic wave focusing in an AIDT structure at 74 MHz frequency. The use of a supercontinuum source for illumination allowed us to choose an optimal spectral width for high-resolution SWLI, resulting in a minimum detectable amplitude limit of less than 100 pm. Furthermore, the short optical pulses enable the characterization of high-frequency microacoustic devices. Consequently, we have pushed the performance of SWLI to new limits in the characterization of surface vibrations in electrically excited microstructures. The vibration characterization capabilities now extend from the typically low-frequency MEMS structures to devices operating in the 100 MHz range and even beyond.

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