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Picosecond supercontinuum light source for stroboscopic white-light interferometry with freely adjustable pulse repetition rate

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Abstract: We present a picosecond supercontinuum light source designed for stroboscopic white-light interferometry. This source offers a potential for high-resolution characterization of vibrational fields in electromechanical components with frequencies up to the GHz range. The light source concept combines a gain-switched laser diode, the output of which is amplified in a two-stage fiber amplifier, with supercontinuum generation in a microstructured optical fiber. Implemented in our white-light interferometer setup, optical pulses with optimized spectral properties and below 310 ps duration are used for stroboscopic illumination at freely adjustable repetition rates. The performance of the source is demonstrated by characterizing the surface vibration field of a square-plate silicon MEMS resonator at 3.37 MHz. A minimum detectable vibration amplitude of less than 100 pm is reached.

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1. Introduction

White-light interferometry (WLI) is a well established and widely used optical method for non-contact 3D profiling of static surface features with a height range extending from the nanometer up to the millimeter scale [1–3]. In contrast to laser interferometry, WLI makes use of a broad spectrum of the light source. The limited coherence length of the light results in a spatially localized interference pattern, which can be used for unambiguous mapping of the surface topography. The broader the light spectrum, the more localized is the fringe pattern. In practice, a minimum coherence length of about $1\mu\text{m}$ can be reached, which enables a surface height determination with a precision of tens of nanometers [3].

The resolution of the surface profiling can, however, be further improved by combining the fringe envelope location measurement with the phase information of the interferometric signal [4]. Through this approach surface height features even down to the sub-nanometer scale can be identified by WLI [4–7]. While broadening the spectrum of the light source does improve the position determination of the fringe envelope, it will decrease the resolution obtainable from the interferometric phase [6]. High-resolution WLI will therefore require a proper composition of the spectral properties of the light source. Even the spectrum of a LED source can actually give a close match to this [8].

White-light interferometry is not, however, restricted to static measurements, but also surface vibration fields can be measured with the use of stroboscopic illumination. Imaging with short enough light pulses, which are synchronized to the surface vibrations, effectively “freezes” the mechanical motion and thus enables the use of static optical profiling techniques [9–11]. By repeating the measurement for different phase delays between the vibrations and the light pulses, periodic vibrational motion can be characterized. Although the technique of high-resolution WLI is well known, many of the published results on stroboscopic WLI have been limited to the measurement of low-frequency (up to a few MHz), high-amplitude (several μm) vibrations with a detection limit of 10 - 100 nm [9, 12, 13].

In order to extend stroboscopic WLI also to the research 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, a significant improvement of the minimum detectable amplitude and also shorter illumination pulses down to the picosecond range are required. As a first step, we have recently achieved a detection limit below 100 pm [8] using LED-based stroboscopic WLI with 8 ns optical pulses. This detection limit is comparable to that of full-field laser interferometry [14] currently employed for vibration measurements at high frequencies. Obtaining significantly shorter pulses with high enough power from such a source remains, however, a technical challenge.

Supercontinuum sources have already demonstrated their potential to stroboscopic WLI with nanosecond long pulses [13]. On the other hand, shorter pulses with spectra extending over a few octaves are typically realized by launching femtosecond pulses from a mode-locked laser into a microstructured optical fiber (MOF). Mode-locked lasers, however, have as a drawback a pulse repetition rate with a narrow tuning range, which is not well suited for the characterization of a wide range of electromechanical devices. Gain-switched laser diodes therefore present a promising alternative as they can provide picosecond optical pulses with freely adjustable repetition rates. Combined with an all-fiber based amplifier, the low-power output of the laser diode can be amplified to high peak-power pulses emitted with excellent beam quality [15–18]. Such a laser source has drawn great interest for many applications, including also the realization of versatile supercontinuum light sources [19–21].

In this paper, we present a supercontinuum light source developed for stroboscopic WLI measurements of vibration fields in electromechanical devices. The source is based on supercontinuum generation (SCG) and it emits broadband picosecond light pulses at a freely adjustable repetition rate up to 50 MHz. The all-fiber pump source consists of a gain-switched laser diode whose output pulses are amplified in a two-stage Ytterbium-doped polarization maintaining fiber (YDPMF) amplifier. A part of the amplified output pulse is frequency doubled and launched together with the remaining fundamental output into a MOF for SCG. Through this dual-wavelength pumping scheme [22, 23] the supercontinuum develops not only in the infrared but generates already at low pump powers a broadband visible part. Here, the visible spectrum is utilized for stroboscopic WLI.

The performance is demonstrated by measuring vibration fields in a square-plate silicon MEMS resonator [24, 25] at 3.37 MHz. A minimum detectable amplitude of less than 100 pm

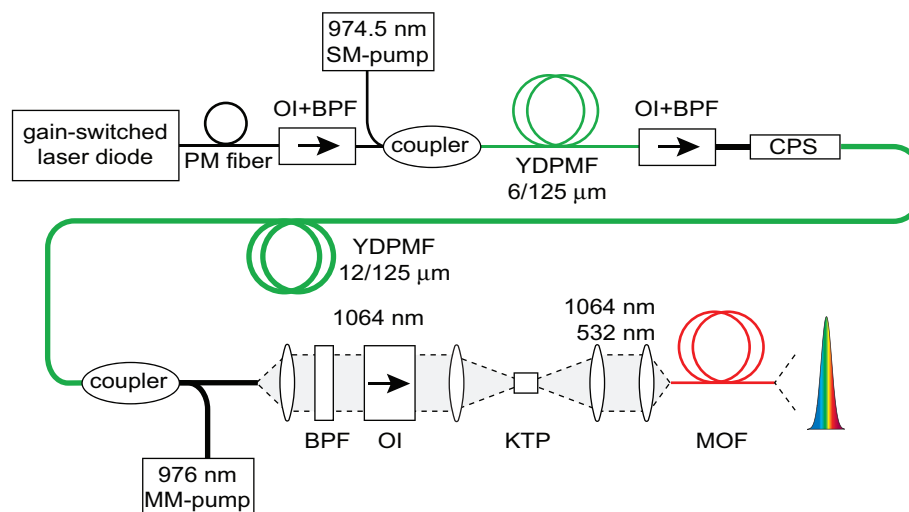


Fig. 1. Schematic diagram of the picosecond supercontinuum light source. Picosecond optical pulses emitted by a gain-switched laser diode are amplified in a two-stage YDPMF amplifier. A part of the amplified optical pulse is frequency doubled in a KTP nonlinear optical crystal before both the 1064 nm and 532 nm wavelengths are coupled into a microstructured optical fiber (MOF). OI - optical isolator; BPF - 1064 nm bandpass filter; CPS - cladding power stripper; SM - single-mode; MM - multi-mode.

is achieved. Together with illumination times shorter than 310 ps, the performance opens up a possibility for characterization of vibration fields even up to the GHz range when illuminating the surface motion at the n th subharmonic of the vibrational frequency, with n being an integer number [13].

2. Supercontinuum source setup and characterization

Tailoring the design of a supercontinuum light source for stroboscopic high-resolution WLI requires both optimized spectral properties as well as a freely adjustable pulse repetition rate over a wide frequency range for vibration field characterization. Ideally, the spectra of the supercontinuum pulses used for WLI should remain unchanged at different pulse repetition rates. This requires that the amplified pulses from the pump source should have the same peak power independent of their repetition rate. Furthermore, their peak power should be balanced, on the one hand, to be sufficiently high for efficient SCG in a MOF, while, on the other hand, their corresponding average power at high repetition rates should remain low in order to minimize heating-induced changes in the free-space coupling to the MOF.

The supercontinuum light source is schematically presented in Fig. 1. The optical pulses emitted from a gain-switched laser diode are amplified in a two-stage, all-fiber, Yb-doped fiber amplifier to kW peak powers. After frequency-doubling a part of the output, optical pulses at 1064 nm and 532 nm are both launched into a MOF to generate a supercontinuum spectrum through a dual-wavelength pumping scheme [22, 23]. Compared to the more than 10 kW typically required for supercontinuum generation with single-wavelength pump pulses at 1064 nm only (see e.g. [20]), coupled pump powers of 1 kW or even less will already be sufficient for visible light generation to wavelengths below 500 nm through this dual-wavelength approach.

The polarization maintaining (PM), fiber-coupled, gain-switched laser diode (PICOPOWER-LD-1064-FC-SF-50, ALPHALAS GmbH) can be synchronized with an external trigger to gen-

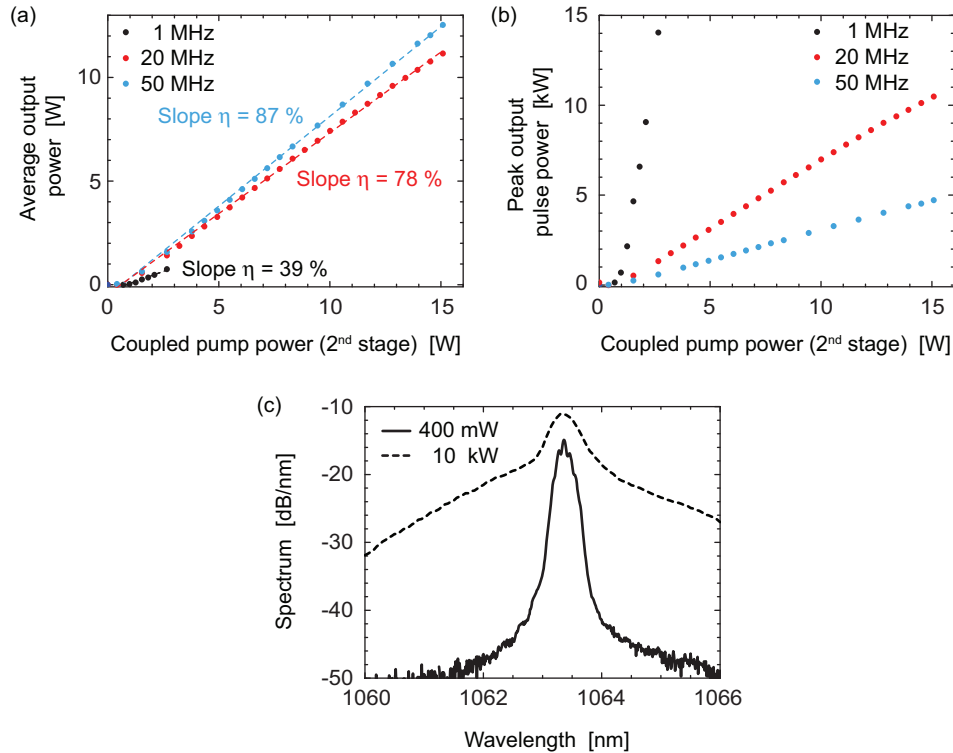


Fig. 2. (a) Measured average and (b) corresponding estimated peak signal output power as a function of the coupled second stage pump power for different pulse repetition rates. (c) The optical spectra of the pulses emitted from the gain-switched laser diode (solid line, 400 mW peak power) and of amplified optical pulses with 10 kW peak power (dashed line) are shown for a pulse repetition rate of 1 MHz.

erate optical pulses at freely selectable repetition rates ranging from a single shot up to 50 MHz. The pulse jitter compared to the external trigger signal is specified to be smaller than 6 ps. The single-frequency laser pulses have the maximum spectral output power at a wavelength of 1063.4 nm with a full-width-half-maximum (FWHM) bandwidth of below 0.25 nm and a temporal pulse width shorter than 50 ps. The average power scales with the selected pulse repetition rate and reaches, for instance, 20 μ W at 1 MHz, which corresponds to a pulse peak power of about 400 mW.

In order to increase the pulse peak powers to the kW range, a two-stage, all-fiber, Yb-doped fiber amplifier was designed. The amplifier chain is directly spliced together to allow for maximum mechanical stability and efficient power coupling. An all-PM-fiber approach is used to ensure stable polarization of the output light. The mode-field diameter in the core is scaled to a value which allows avoiding possible nonlinear spectral broadening already in the amplifier chain, while still maintaining a single-mode operation. A fiber-coupled PM optical isolator combined with a 1064 nm-bandpass filter precedes each amplification stage to prevent the backward propagation of light and to reduce the amount of amplified spontaneous emission.

The first amplifier stage consists of a 1.0 m long single-mode YDPMF (core mode-field diameter: 6.0 μ m; cladding diameter: 125 μ m; LIEKKITM Yb700-6/125-PM) which is core-pumped in forward direction at a wavelength of 974.5 nm with a fiber-Bragg-grating-stabilized single-mode pump laser module. The amplifier stage provides at a coupled pump power of

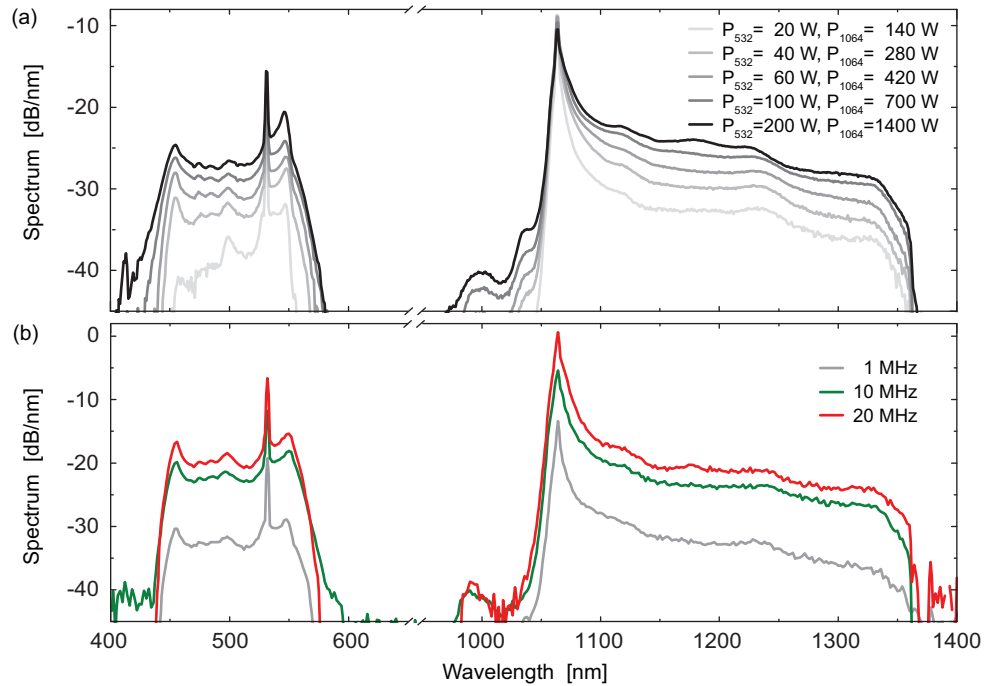


Fig. 3. Supercontinuum spectra measured for (a) different coupled peak powers at a pulse repetition rate of 1 MHz and (b) different pulse repetition rates at a coupled peak power of $P_{532} = 60$ W and $P_{1064} = 420$ W, showing that the shape of the spectra remain constant.

140 mW a gain of 15 dB to optical pulses at 1 MHz.

The second stage is a 2.5 m long single-mode double-cladding YDPMF with an increased fiber core diameter of $12.5 \mu\text{m}$ (cladding diameter: $125.0 \mu\text{m}$; LIEKKI™ Yb1200-12/125DC-PM). The active fiber is cladding-pumped in backward direction by a multimode pump laser module at a wavelength of 976.0 nm. The average output powers measured for three selected pulse repetition rates are presented in Fig. 2(a) as a function of the second stage coupled pump power. The emitted average power exceeds 12 W at 50 MHz and a coupled pump power of 15 W, corresponding to a gain of about 30 dB and a slope efficiency of 87 %. In comparison, at 1 MHz a similar gain is already reached at a coupled pump power of 2.6 W. The slope efficiency, however, decreases with decreasing pulse repetition rate due to amplified spontaneous emission. The respective pulse peak powers at the amplifier output are estimated from the measured average powers by assuming a Gaussian-shaped temporal pulse profile and a temporal pulse width of 50 ps, see Fig. 2(b). The laser source generates picosecond optical pulses with peak powers exceeding 5 kW up to repetition rates of 50 MHz. By decreasing the pulse repetition rate, even higher peak powers can be achieved, reaching, for instance, at 1 MHz up to 15 kW. Nonlinear spectral broadening in the amplifier is under these conditions largely avoided. For instance, at a peak power of 10 kW, the spectral width of the pulses is only increased by a factor of two compared to the output spectrum of the gain-switched laser diode (Fig. 2(c)).

The light emitted from the last amplifier stage is collimated and then passed through a free-space 1064 nm bandpass filter and optical isolator. Subsequently, a part of the output is frequency-doubled in a 5 mm long KTP crystal with a conversion efficiency of about 22 %. Both the 532 nm and 1064 nm wavelengths are then coupled into a 7 m long MOF using a microscope objective. The coupling of the wavelengths into the MOF depends on the objective's

transmission and on the longitudinal fiber alignment due to chromatic aberration of the objective, yielding at the input of the MOF approximately an efficiency of 9% at 532 nm and 17.5% at 1064 nm for the presented measurements. The geometry of the custom made silica MOF (triangular grid of holes with pitch $\Lambda = 1.55\mu\text{m}$ and relative hole size of $d/\Lambda = 0.7$) has been chosen such that the first zero dispersion wavelength is located between the two pump wavelengths at 778 nm (see also [23]). The inverse group velocity β_1 and the group velocity dispersion β_2 are $\beta_1 = 4.985 \cdot 10^{-9}$ s/m and $\beta_2 = -5.079 \cdot 10^{-26}$ s²/m at 532 nm and $\beta_1 = 4.971 \cdot 10^{-9}$ s/m and $\beta_2 = -5.652 \cdot 10^{-26}$ s²/m at 1064 nm.

The measured spectra at the output of the MOF are shown in Fig. 3(a) for different coupled peak powers at a pulse repetition rate of 1 MHz. The infrared pump at 1064 nm initiates the generation of a continuum towards longer wavelengths only, driven by soliton dynamics. In the visible, however, the interaction of the infrared solitons with the visible pump causes the development of a blue-shifted continuum down to about 450 nm through cascaded cross-phase modulation [23]. Above coupled peak powers of $P_{532} = 40$ W and $P_{1064} = 280$ W for the 532 nm and 1064 nm pump pulses, respectively, the wavelength dependence of the spectra remains almost independent of the pump power. Furthermore, comparing the supercontinuum spectra measured at different pulse repetition rates in Fig. 3(b), nearly identical spectra at a given coupled pulse peak power ($P_{532} = 60$ W and $P_{1064} = 420$ W) are recorded, only with an increased power spectral density. The supercontinuum source allows operation both in the infrared and the visible, depending on the application.

3. Application of the source to stroboscopic high-resolution white-light interferometry

The supercontinuum light source is incorporated into our existing Michelson-type white-light interferometer setup [8] as illustrated in Fig. 4. The optical pulses emitted from the supercontinuum source are first spectrally filtered with a 40 nm-broad (FWHM) bandpass filter centered at 500 nm in order to optimize the spectral properties for high-resolution WLI. The filtered light is guided through a 2 m long multi-mode optical fiber, which serves to reduce speckle noise and to eliminate spatial dependence of the spectral properties before entering the interferometer. Measured average temporal and spectral properties of the illuminating light pulses at 1 MHz repetition rate ($P_{532} = 60$ W and $P_{1064} = 420$ W) are presented in the insets of Fig. 4. The temporal shape of the illuminating pulse as incident on the sample (see Fig. 4(a)) was recorded with a high speed photodetector (Newport Model 877), having a specified rise and fall time below 200 ps, and a 13 GHz-bandwidth oscilloscope (Agilent Infiniium DSO91304A, 40 Gs/s). The measured pulse width of 310 ps (FWHM) is therefore significantly influenced by the detector performance and can be considered as the upper limit. This is in agreement with an estimated temporal pulse width of less than 200 ps, which was obtained by solving the generalized nonlinear Schrödinger equation for the pulse propagating through the MOF and by calculating the temporal broadening caused by modal-dispersion in an idealized multi-mode optical fiber. The pulse spectrum, shown in Fig. 4(b) in linear scale, is centered at 500 nm and extends over approximately 40 nm (FWHM).

The performance of the supercontinuum source in a stroboscopic WLI application is demonstrated by measuring the surface vibration fields in a piezo-electrically actuated square-plate silicon MEMS resonator [24, 25]. To enable comparison with our previous results obtained by LED-based stroboscopic WLI [8], the same sample and vibration mode at 3.37 MHz were characterized. The data analysis is based on the frequency domain approach followed by vibration analysis [8] and yields from the WLI data the amplitude and phase fields of the surface vibration as shown in Fig. 5(a) and (b), respectively. The amplitude and phase data can be combined to construct an instantaneous 3D view of the surface deformation at any phase of the vibration, allowing also animation of the surface vibration. Exemplarily, a 3D view with the center

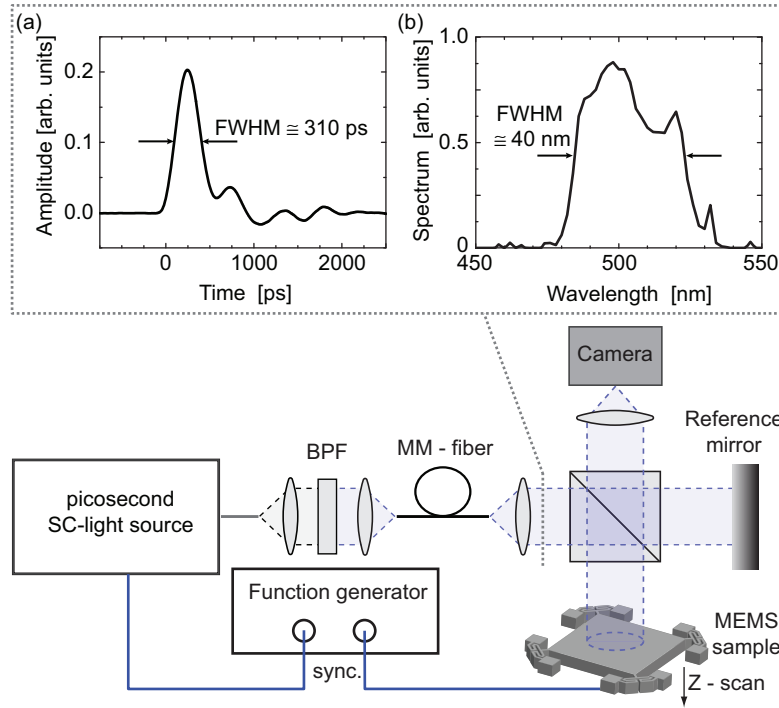


Fig. 4. The supercontinuum optical pulses emitted by the source are first spectrally filtered by a bandpass filter (BPF) and guided through a multi-mode fiber (MM-fiber) before illuminating the sample in our stroboscopic white-light interferometer setup. A function generator drives the MEMS sample and provides the synchronization signal for the light source. The insets show the measured average (a) temporal and (b) spectral properties of the optical pulses at the interferometer input at 1 MHz repetition rate.

of the plate at its maximum deflection is presented in Fig. 5(c) above a schematic view of the plate-resonator.

The results are identical with those reported earlier for the same 3.37 MHz vibration mode, except for the slightly larger maximum amplitude observed here, which is attributed to a small difference in the electrical driving condition together with an improved vacuum at the sample. The nodal line in the amplitude data allows us to estimate that a similar minimum detectable amplitude limit of less than 100 pm is reached. This demonstrates that the spectral properties of the illuminating pulses from the supercontinuum source are well suited for high-resolution WLI. In this comparison with our previous LED-based results, the more than an order of magnitude shorter illumination pulses were not completely taken advantage of. The short pulses are, however, essential for the characterization of vibration fields at much higher frequencies.

4. Conclusions

We have presented the concept and performance of a picosecond pulsed supercontinuum light source which has been developed for stroboscopic high-resolution white-light interferometry.

The optical spectrum of the supercontinuum pulses allows, in principle, the operation both in the infrared and the visible. While here only the visible part of the generated supercontinuum spectrum was utilized for stroboscopic white-light interferometry, the infrared part could, for instance, find application in through-silicon characterization of static or dynamic electrome-

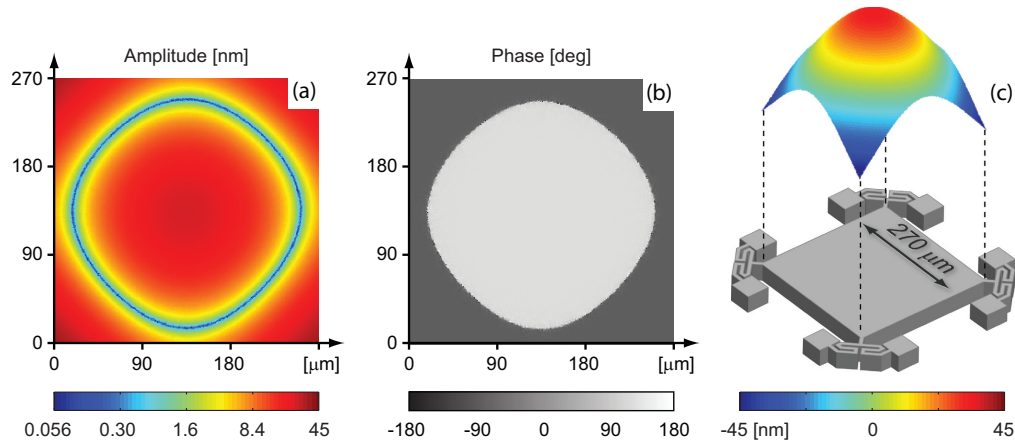


Fig. 5. The measured (a) amplitude and (b) phase data for the 3.37 MHz vibration mode are presented. In (c) a schematic view of the square-plate silicon MEMS resonator is shown together with a 3D view of the instantaneous surface deformation obtained by combining amplitude and phase data at maximum deflection of the plate center.

chanical devices [26]. The presented spectral properties of the light source enabled us to obtain high resolution surface profiles by taking advantage of both the interferometric fringe localization in low-coherence interferometry and the phase information of the interferometric signal. The achieved minimum detectable amplitude of less than 100 pm corresponds to the current state-of-the-art level obtained in stroboscopic WLI and is comparable to the performance of full-field laser interferometry [14].

Our approach enables freely adjustable pulse repetition rates up to 50 MHz in synchronization with a vibration frequency of interest. Importantly, the optical pulses used for the stroboscopic illumination were measured to be shorter than 310 ps.

The picosecond illumination pulses together with the excellent amplitude resolution, opens up a possibility to utilize stroboscopic white-light interferometry for the study of high-frequency vibration fields in electromechanical devices even up to the GHz range.

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