Supplementary

1. OPA and cantilever synchronous driving for resonant beam scanning demonstration

The architecture of the OPA characterization bench used in this work has been presented in previous publications [1,2]. It is based on a standard 300mm probing station (Cascade Elite 300) typically used in the microelectronic industry for wafer-level circuit testing. In order to characterize the scanning properties of the OPA circuit while driving the cantilever in a resonant state, a specific control system has been used. A schematic view of the setup is presented on Figure 1(a). The cantilever PZT actuator is driven by a sinusoidal signal coming from a 3 channel Arbitrary Waveform Generator (AWG, Spectrum Instrumentation DN2.656-16). The light from a pulsed laser (Aerodiode Shaper with Fabry-Perot laser diode) is coupled to an optical fiber and passes through a variable attenuator (not shown) and a fiber polarization controller (FPC) before being injected at the OPA input using a grating coupler. The emission of a light pulse from the laser is controlled by an external trigger signal generated by the AWG. The 16 phase shifters (thermo-optical modulators) of the OPA are individually controlled by a custom made electronic board (OPA control board). In order to limit the power dissipation due to the heat generated by the thermo-optical modulators, the output of the control board is operated in a pulsed regime where the 16 electrical channels are being enabled/disabled by a periodic square signal generated by the AWG. Due to space constraints, the OPA far field emission is imaged directly on the bare sensor of a CCD camera (Allied Vision Prosilica GT 6600) with no intermediate lenses. All of the instruments are controlled by a master computer and Python programs.

In order to take an instantaneous / frozen image of the emitted beam while the cantilever is dynamically actuated, we rely on the Strobe effect by synchronizing all the control signals emitted by the AWG as presented in Figure 1(b). A sinusoidal signal drives the cantilever at its resonant frequency $f_{cant} = 1.52kHz$. The laser pulses are generated with a repetition rate that correspond to an integer lower multiple (60) of the cantilever driving frequency $f_{las\_heat} = f_{cant}/60 = 25.33Hz$, thus the cantilever is always in the same position when a light pulse is sent to the OPA. In addition, the emission of the laser pulses must be synchronized with the activation of the phase modulators, so that the emitted light will be shaped by the OPA. Thus, the square signal that drives the activation of the OPA modulators have the same frequency as the laser driving signal f_{las_heat}. The electrical pulse duration is set to $\tau_c \approx 30\mu s$, and the laser pulse is sent with a delay $\Delta_{las} \approx 20\mu s$ that is slightly larger than the thermo-optical modulator response time (corresponding to a cutoff frequency of ~50kHz). Finally, the imaging camera (that cannot be synchronized, no external trigger input) integration time is set to a value corresponding to the laser repetition rate, thus avoiding image blinking $Integ_{camera} = 1/f_{las\_heat} = 39474\mu s$. Thus, only a single laser pulse is exposed on each picture captured by the camera. The laser output power is then adapted using the variable attenuator to avoid saturation of the camera.

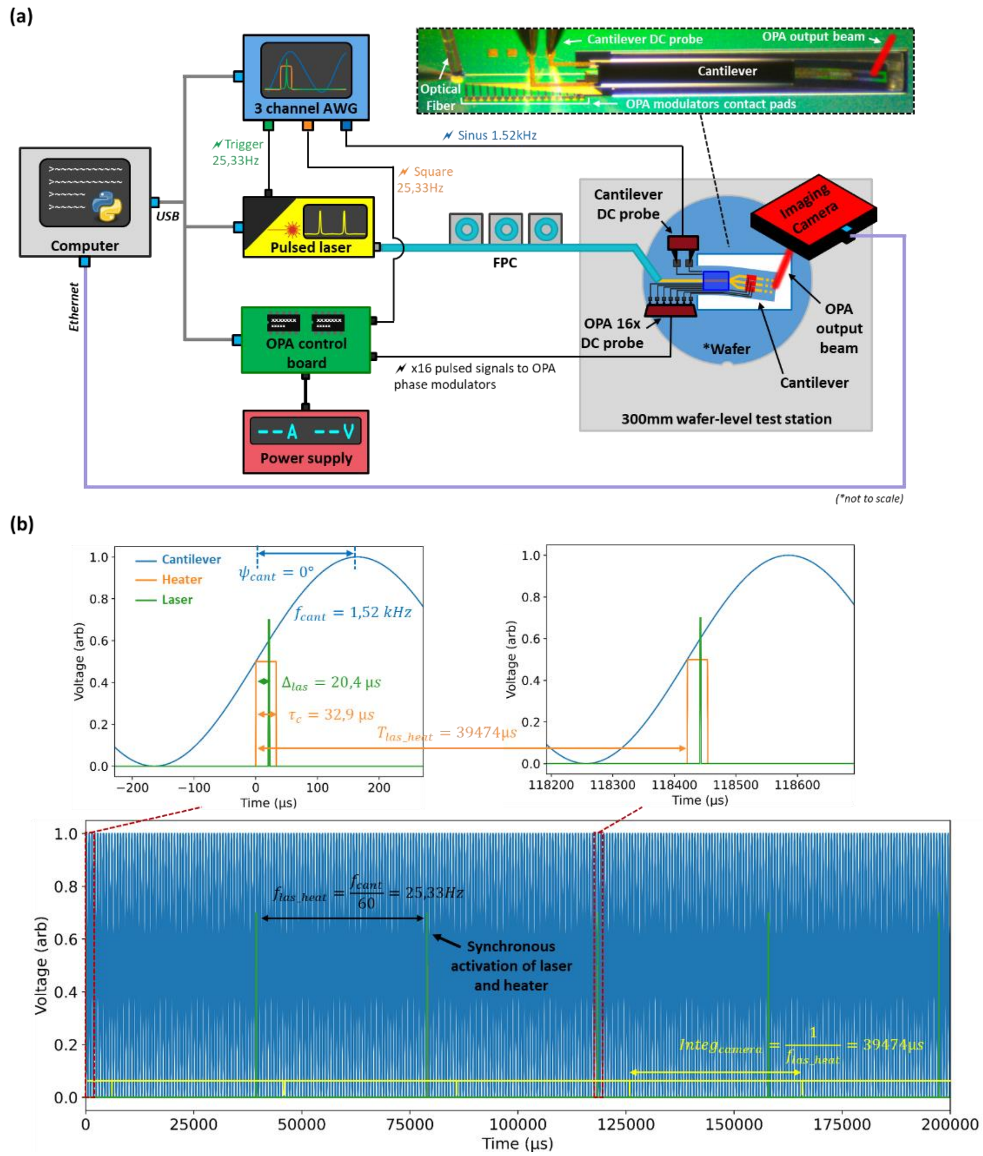

Figure 1, (a) Schematic of the OPA and cantilever synchronous driving system. (b) Temporal view of the different synchronization signals generated by the AWG.

Therefore, by tuning the phase ψ_{cant} of the sinusoidal driving signal (that corresponds to a relative time shift with the laser/heater activation), we are able to capture an image with the cantilever in a certain position. This technique was used to acquire the composite image presented in Figure 2, demonstrating the 2D scanning capability of the cantilever-OPA. The cantilever is excited at its resonant frequency and the driving signal phase is set to a certain value, fixing the beam output angle on the θ axis. Then, the OPA is operated to scan the beam on the ϕ axis and images are taken at some discrete angles (here +/-10°, 2° steps). Then the driving signal phase is changed (here from 160 to 300°), and the OPA scanning process is repeated. The phase value are chosen to fully map the cantilever scanning range. Then, all the acquired images are stacked (individual pixel summation) in order to get the composite image.

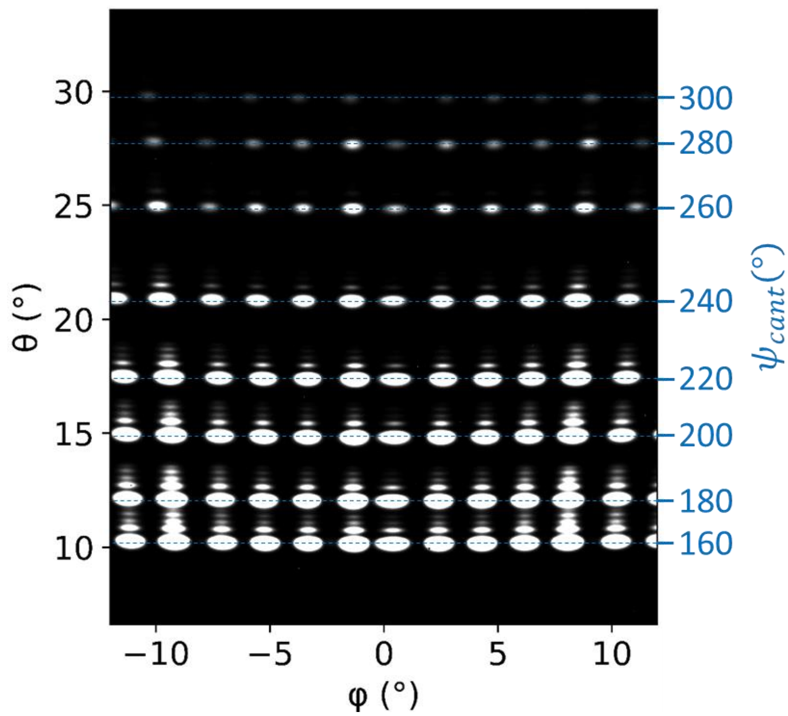

Figure 2, Composite image of the OPA output configured for various main beam emission in φ and θ while the cantilever is excited at its resonance frequency fcant = 1.52 kHz.

2. Long exposure acquisition to measure the maximum beam scanning amplitude in the AC regime

As presented on Figure 3(a), we used some long exposure images ($Integ_{camera} \gg 1/f_{cant}$) in order to measure the minimum θ_{min} and maximum θ_{max} deflection of the output beam on the θ axis. Light is injected inside the OPA, the cantilever is excited with a sinusoidal signal corresponding to its resonant frequency ($f_{cant} = 1.52kHz$) and a long exposure image is taken. The extracted beam scanning amplitude as a function of the cantilever driving signal voltage amplitude is presented Figure 3(b). First (region I), both θ_{min} and θ_{max} are increasing/decreasing linearly with the driving signal voltage amplitude (expected behavior). However for a voltage >6V (region II), the measured θ_{max} stops increasing and is fixed at ~28° (while θ_{min} continues to decrease linearly). As shown on the drawings I and II on Figure 3(c), this unnatural behavior is due to the output beam being obscured by the wall of the cantilever cavity (insufficient spacing between the cantilever tip and the end of the cavity). This issue can be solved simply by engraving a wider area in front of the cantilever. This also explains why the output beam intensity decreases with increasing θ angle (see Figure 2), the light emitted by the OPA antennas is gradually shaded while the cantilever is going down towards the substrate (increasing θ). Thus, the maximum measured beam scanning amplitude is $\Delta\theta \approx$ 26° (@ 16V). Using projection of the linear fit on the first part of the θ_{max} curve, we can compute the "hidden θ_{max}" which gives a maximum beam scanning amplitude $\Delta\theta \approx 42°$. Finally, when the voltage is further increased (>16V), catastrophic failure occurred, with the dielectric breakdown of the PZT actuator (region III Figure 3(b)). The origin of this damage remains under investigation, but it is likely that doping with La or Nb, can help increase resistance to dielectric breakdown of the PZT layer [3].

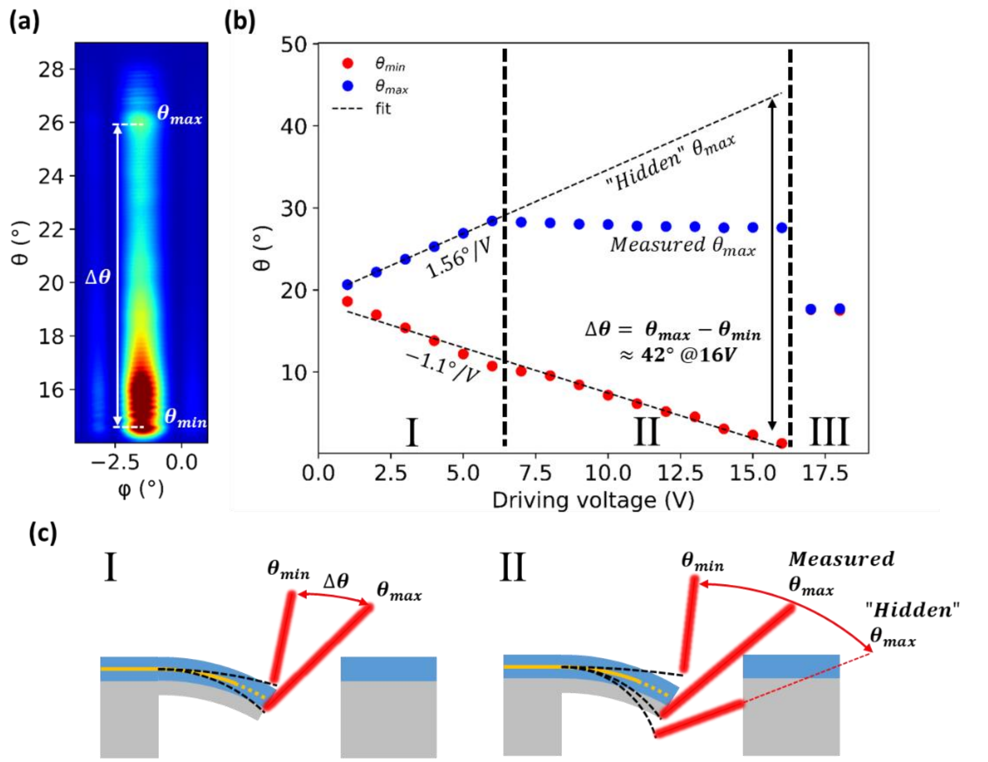

Figure 3, (a) Long exposure image of the OPA output beam while the cantilever is moving due to the electrical excitation. (b) Measured maximum beam scanning amplitude on the cantilever (θ) axis.

References

1. S. Guerber, D. Fowler, I. Charlet, P. Grosse, K. Abdoul-Carime, J. Faugier-Tovar, and B. Szelag, "Development, calibration and characterization of silicon photonics based optical phased arrays," in *Smart Photonic and Optoelectronic Integrated Circuits XXIII* (SPIE, 2021), Vol. 11690, pp. 22–29.
2. S. Guerber, D. Fowler, J. Faugier-Tovar, K. A. Carim, B. Delplanque, and B. Szelag, "Wafer-level calibration of large-scale integrated optical phased arrays," Opt. Express, OE **30**, 35246–35255 (2022).
3. N. Barrett, I. Gueye, G. L. Rhun, O. Renault, and E. Defay, "Unexpected band-bending of donor-doped PbZr0.52Ti0.48O3 films," Thin Solid Films **715**, 138423 (2020).