Spectrally Broadband Electro-Optic Modulation with Nanoelectromechanical String Resonators

Nicolas Cazier, Pedram Sadeghi, Miao-Hsuan Chien, Mostafa Moonir Shawrav, and Silvan Schmid

Institute of Sensor and Actuator Systems, TU Wien, 1040 Vienna, Austria.

(Dated: December 23, 2019)

In this paper, we present an electro-optical modulator made of two parallel nanoelectromechanical silicon nitride string resonators. These strings are covered with electrically connected gold electrodes and actuated either by Lorentz or electrostatic forces. The in-plane string vibrations modulate the width of the gap between the strings. The gold electrodes on both sides of the gap act as a mobile mirror that modulate the laser light that is focused in the middle of this gap. These electro-optical modulators can achieve an optical modulation depth of almost 100% for a driving voltage lower than 1 mV at a frequency of 314 kHz. The frequency range is determined by the string resonance frequency, which can take values of the order of a few hundred kilohertz to several megahertz. The strings are driven in the strongly nonlinear regime, which allows a frequency tuning of several kilohertz without significant effect on the optical modulation depth.

I. INTRODUCTION

In recent years, optomechanical systems have generated a lot of interest [1][3], in part because of their many applications as sensors for precision measurements [4][5], but also because of their usefulness as reconfigurable metamaterials [6][11] and as plasmon-mechanical resonators [12][13]. Among nanomechanical resonators, silicon nitride (SiN) strings and membranes stand out because of their very high quality factors, which make them very useful for experimenting on cavity optomechanics [10][21], or for designing sensors [15][18][22][23] and optomechanical systems [12][14][15][18].

In particular, reconfigurable metamaterials made of arrays of silicon nitride string resonators have been demonstrated as effective electro-optic modulators, where the strings were actuated using either electrostatic forces [6], Lorentz forces [9], or electrostriction [11]. However, these metamaterial-based electro-optical modulators suffer from having either low optical modulation depths [9] or requiring high driving voltages [6][11].

In this paper, we present a different kind of electro-optical modulator, made of two gold covered and electrically connected silicon nitride string resonators, separated by a small gap in their center, similar to the structures used by Thijssen et al. in Ref. [12], but actuated electromagnetically using Lorentz forces to change the width of the gap between the strings, by driving one of the strings at the resonance frequency of its in-plane fundamental mode. When a laser is focused in the middle of the gap, we can use this to modulate the reflection of this laser on the gold electrode covering the string. This gives us an easy way to fabricate MEMS electro-optical modulators with an optical modulation depth that can reach almost 100% for a driving voltage below 1 mV. We also tested similar structures that were actuated using electrostatic forces (generated by comb-drive actuators between the strings) instead of Lorentz forces, and achieved an optical modulation depth of 82% for a driving voltage of 250 mV for the electro-optical modulators based on these structures.

II. METHODS

The wafer used to fabricate our optomechanical resonators was a 380 µm thick silicon wafer, covered on both sides by a 300 nm thick layer of low stress (200 MPa) LPCVD Si3N4. The fabrication process was then done in three steps. First we deposited the gold electrodes using UV lithography, followed by thermal evaporation of a 100 nm thick gold layer and then lift-off. In the second step, the silicon nitride strings were created by UV lithography, followed by Reactive Ion Etching (RIE) of the silicon layer. The last step was to use dry etching with XeF2 to etch the silicon substrate over a depth of 6 µm in order to release the Si3N4 strings. At the end of the fabrication process, the width of the gap between the strings was between 0.55 µm and 1.65 µm depending on the sample measured (see Fig. 1a). During all our measurements, the laser was initially focused on the middle of this gap between the two strings.

The experimental setup used can be seen on Fig. 1b. The laser used is a Titanium-Sapphire laser (SolsTiS from M Squared), whose wavelength can be tuned from 730 nm to 1000 nm. The wavelength chosen for our measurements was 730 nm. The sample is placed in a vacuum chamber between two neodymium magnets that create a static magnetic field of about B = 200 mT at the center of the sample. The waveplate and linear polarizers are used to adjust the laser optical intensity as well as its polarization, which we chose to be parallel to the strings during our measurements. The laser optical power when it reaches the sample is 38 µW. A lock-in amplifier (UHFLI from Zurich Instruments) is used to send an oscillating current through one of the strings and detect the resulting variation in the reflected laser optical power using a silicon avalanche photodetector (APD410A/M from...
III. RESULTS

We measured three different samples using Lorentz forces actuation, with different lengths for the string resonators. The first sample had strings with a length \(L = 100 \mu m\) and a gap width of 0.55 \(\mu m\). Its fundamental resonance frequency for the in-plane mode is 1.494 MHz, and the resonance has a quality factor of 3000. The string resistance \(R = 140 \Omega\), which gives us, for a driving voltage \(V_{AC} = 15 \text{ mV}\), a maximal Lorentz force \(F_L = L \times B \times V_{AC}/R = 2.14 \text{ nN}\). The displacement of the string, as measured from the change in the reflected laser power, is then large enough to present a very strong mechanical nonlinearity, as can be seen on Fig. 2a, which shows a distortion of the resonance peak of the string typical of a nonlinear Duffing resonator [24]. However, unlike the theoretical nonlinear Duffing resonator, there seems to be a maximal driving voltage beyond which the resonance peak shape and amplitude no longer change. This maximal voltage is 15 mV here, but we observed a similar behavior for lower voltages in our other samples. We think this may correspond to the driving voltage where the gap between the strings close completely, which would prevent the string displacement from increasing even further. The width of the nonlinear resonance peak at higher driving voltages also means we can adjust the modulation frequency of our electro-optical resonator by a few kilohertz without losing much of the reflected signal amplitude.

The red curve on Fig. 2b represents the electro-optical modulation of the reflected laser power as a function of time, measured when driving the string with a voltage \(V_{AC} = 15 \text{ mV}\) and a resonance frequency of 1.497 MHz, close to the peak maximum. The modulated signal here is quasi-sinusoidal, and has an optical modulation depth of 35.4 %, which is the maximum we could obtain for this sample. However, we can obtain much higher optical modulation depths at lower driving voltages if we use longer strings because of their lower effective spring constant. For example, the second sample we measured had strings with a length of 300 \(\mu m\), an electrical resistance of 250 \(\Omega\) and a gap width of 1.65 \(\mu m\). The fundamental resonance frequency for the in-plane mode is then 314 kHz, with a quality factor of 6800. When driving this string at its fundamental resonance frequency with a voltage \(V_{AC} = 1 \text{ mV}\) (corresponding to a Lorentz force \(F = 240 \text{ pN}\)), we can then obtain an optical modulation depth of 99.6 % for the reflected laser power (see the blue curve on Fig. 2b), although the modulated signal is no longer quasi-sinusoidal here. We had similar results for our third measured sample, which had strings with a length of 500 \(\mu m\), an electrical resistance of 300 \(\Omega\) and a gap width of 1.6 \(\mu m\). This time the fundamental resonance frequency for the in-plane mode is 166 kHz, with a quality factor of 7900, and we were able to obtain an optical modulation depth of 98.9 % (see the green curve on Fig. 2b) for the reflected laser power, with a driving voltage of only 0.25 mV (corresponding to a Lorentz force of 70 pN).

The maximal reflected laser power we measured (for the sample with the 300 \(\mu m\) long strings) is 32.1 \(\mu W\) for an incident laser power of 38 \(\mu W\), which gives us a maximal reflection coefficient of 84.5 %, close to the theoretical reflectivity of gold of 90 % for a wavelength of 730 nm [25], so our electro-optical modulators seem to present very little losses. We can also note that the power consumption for these electro-optical modulators is very low : \(P = \frac{1}{2}V_{AC}^2/R = 0.8 \mu W\) for \(V_{AC} = 15 \text{ mV}\) in the case of the 100 \(\mu m\) long strings, \(P = 2 \text{ nW}\) for \(V_{AC} = 1 \text{ mV}\) in the case of the 300 \(\mu m\) long strings and \(P = 87 \text{ pW}\) for \(V_{AC} = 0.25 \text{ mV}\) in the case of the 500 \(\mu m\) long strings.

If we compare our electro-optical modulators to reconfigurable metamaterial-based modulators, as e.g. [9], which are also actuated using Lorentz forces, we can note that we were able to improve the optical modulation depth from a few % up to 35 % to 100 % for a driving voltage of 15 mV to 0.25 mV. Also, unlike with metamaterial-based electro-optical modulators, whose transmission and reflection coefficients strongly depend on the laser wavelength, our electro-optical modulators will in theory have a reflection coefficient and an optical modulation depth that are quasi-independent of the laser wavelength used, at least for wavelengths above 650 nm where the reflectivity of gold is always above 90 % [25].

To remove the bulky pair of magnets which is used to create the magnetic field for Lorentz force actuation, we also fabricated a sample with strings that could be driven with electrostatic forces using comb-drive actuators placed between the two strings (see Fig. 3a for the SEM picture), since this kind of electro-optical modulators would be easier to integrate. This sample has strings of length 600 \(\mu m\) with a gap width of 1.25 \(\mu m\). The fundamental resonance frequency for the in-plane mode is 102 kHz and its quality factor is 9800.

The electrostatic force created by the Comb-Drive actuators is theoretically equal to \(F_{EL} = N \varepsilon_0 h_{Au}/D_{EL} \times V^2\), with \(N = 24\) the number of electrodes, \(D_{EL} = 3 \mu m\) the distance between the electrodes, \(h_{Au} = 100 \text{ nm}\) the thickness of the gold layer and \(\varepsilon_0 = 8.85 \text{ pF/m}\) the vacuum permittivity [26]. Since the electrostatic...
force is proportional to $V^2$, we cannot just apply directly a voltage $V = V_{AC}\cos(\omega t)$ to our strings, as the force would be proportional to $V^2 = V_{AC}^2\cos^2(\omega t) = \frac{1}{2}V_{AC}^2(1 + \cos(2\omega t))$ and oscillate at twice the resonance frequency. By applying a DC voltage as well as an AC voltage like this: $V = V_{DC} + V_{AC}\cos(\omega t)$, we can have $V^2 = V_{DC}^2 + \frac{1}{2}V_{AC}^2 + 2V_{DC}V_{AC}\cos(\omega t) + \frac{1}{2}V_{AC}^2\cos(2\omega t)$, where the component of the electrostatic force in $\cos(\omega t)$, the only one that can excite the fundamental in-plane mode, will be proportional to $2V_{DC}V_{AC}$. For $V_{DC} = 500$ mV and $V_{AC} = 250$ mV, this gives us an electrostatic force equal to $F_{EL} = k_0a_0/D_{El} \times 2V_{DC}V_{AC} = 1.77$ pN. This value is much lower than for the Lorentz forces, but unlike the Lorentz forces that are uniformly applied to the whole length of the string, the electrostatic forces are only applied to the middle part of the string and are therefore going to be much more efficient.

This sample was driven with a DC voltage $V_{DC} = 500$ mV and a AC voltage between 20 mV and 250 mV, this time applied to both ends of the electrode on one string, with the electrode on the other string being grounded, so no current was able to flow through the string’s electrodes. Similarly to the previous samples actuated with Lorentz forces, we could easily detect an electro-optical modulation of the reflected laser power, with an optical modulation depth of 82.3 % for $V_{AC} = 250$ mV (see Fig. 2b). However, like for our previous samples, there seems to be a specific driving voltage beyond which the maximal displacement of the string seems to saturate, or at least no longer increases linearly with the AC voltage used to drive the string, unlike what we would expect: When we increase $V_{AC}$ from 20 mV to 250 mV, the maximal amplitude of the reflected laser power only increases from 14 µW to 20 µW. This gives us a maximal reflection coefficient of 52.6 % for 22 µW, which is still below the maximal reflection coefficient of 84.5 % we measured for the samples using Lorentz forces actuation.

Still, this is quite a good result, and shows that electrostatic forces would be a viable alternative to Lorentz forces for actuating these electro-optical modulators. Indeed, compared to similar reconfigurable metamaterial-based electro-optical modulators that are also actuated using electrostatic forces [6], our design constitutes a significant improvement in reversible modulation of the reflectance.

**IV. CONCLUSION**

To summarize our results, we showed in this paper that electromagnetically-actuated, gold covered silicon nitride string resonators could be efficiently used to make MEMS electro-optical modulators, with an optical modulation depth easily reaching almost 100 % for a driving voltage below 1 mV and a power consumption below 2 mW. The modulation frequency is determined by the length of the string resonator, but can go from 100 kHz up to 1.5 MHz. However, the shorter string resonators needed for the higher modulation frequencies also have lower quality factors and therefore lower optical modulation depths, and will need higher driving voltages as well. These electro-optical modulators can be easily fabricated with standard microfabrication techniques, which would make them easy to integrate on-chip into a wider micro-opto-electro-mechanical system.

**ACKNOWLEDGMENTS**

We would like to thank our technician Sophia Ewert for her cleanroom support. This work has also received funding from the European Research Council under the European Unions Horizon 2020 research and innovation program (Grant Agreement-716087-PLASMECS).

[1] Ivan Favero and Khaled Karrai. Optomechanics of Deformable Optical Cavities. *Nature Photonics*, 3(4):201–205, 2009.

[2] Jordi Gomis-Bresco, Daniel Navarro-Urrios, Mourad Oudich, Said El-Jallal, Amadeu Griol, Daniel Puerto, Emiglio Chavez, Yan Pennc, Bahram Djaafari-Rouhani, Francesca Alzina, Alejandro Martinez, and Clivia. M. Sotomayor Torres. A 1D Optomechanical Crystal with a Complete Phononic Band Gap. *Nature Communications*, (5):4452, July 2014.

[3] Markus Aspelmeyer, Tobias J Kippenberg, and Florian Marquardt. Cavity Optomechanics. *Reviews of Modern Physics*, 86(4):1391–1452, 2014.

[4] Tolga Bagci, Anne Simonsen, Silvan Schmid, Luis Guillermo Villanueva, Emil Zeuthen, J. Appel, Jacob M. Taylor, Anders Sorensen, Koji Usami, A. Schliesser, and Eugene S. Polzik. Optical Detection of Radio Waves Through a Nanomechanical Transducer. *Nature*, 507(7490):81–85, March 2014.

[5] Markus Piller, Niklas Luhmann, Miao-Hsuan Chien, and Silvan Schmid. Nanoelectromechanical Infrared Detector. *Proceedings of SPIE*, 11088, 2019.

[6] Jun-Yu Ou, Eric Plum, Jianfa Zhang, and Nikolay I. Zheludev. An electromechanically reconfigurable plasmonic metamaterial operating in the near-infrared. *Nature Technology*, 8(4):252–255, April 2013.

[7] Jun-Yu Ou, Eric Plum, Jianfa Zhang, and Nikolay I. Zheludev. Giant Nonlinearity of an Optically Reconfigurable Plasmonic Metamaterial. *Advanced Materials*, 28:729–733, 2016.

[8] Biqin Dong, Xiangfan Chen, Fan Zhou, Chen Wang, Hao F. Zhang, and Cheng Sun. Gigahertz All-Optical Modulation Using Reconfigurable Nanophotonic Metamolecules. *Nano Letters*, 2016.

[9] Joao Valente, Jun-Yu Ou, Eric Plum, Ian J. Youngs, and Nikolay I. Zheludev. A Magneto-Electro-Optical Effect in a Plasmonic Nanowire Material. *Nature Communications*, 6(7021), 2015.
Nikolay I. Zheludev and Eric Plum. Reconfigurable Nanomechanical Photonic Metamaterials. *Nature Nanotechnology*, 11(1):16–22, January 2016.

Artemios Karvounis, Behrad Gholipour, Kevin F. MacDonald, and Nikolay I. Zheludev. Giant Electro-Optical Effect through Electrostriction in a Nanomechanical Metamaterial. *Advanced Materials*, 31:1804801, 2019.

Rutger Thijssen, Ewald Verhagen, Tobias J. Kippenberg, and Albert Polman. Plasmon Nanomechanical Coupling for Nanoscale Transduction. *Nano Letters*, 13(7):3293–3297, July 2013.

Rutger Thijssen, Tobias J. Kippenberg, Albert Polman, and Ewald Verhagen. Parallel Transduction of Nanomechanical Motion Using Plasmonic Resonators. *ACS Photonics*, 1(11):1181–1188, November 2014.

Rutger Thijssen, Tobias J. Kippenberg, Albert Polman, and Ewald Verhagen. Plasmonomechanical Resonators Based on Dimer Nanoantennas. *Nano Letters*, 15(6):3971–3976, June 2015.

Silvan Schmid, Kaiyu Wu, Peter Emil Larsen, Tomas Rindzevicius, and Anja Boisen. Low-Power Photothermal Probing of Single Plasmonic Nanostructures with Nanomechanical String Resonators. *Nano Letters*, 14(5):2318–2321, May 2014.

Denys Naumenko, Valeria Toffoli, Silvio Greco, Simone Dal Zilio, Alpan Bek, and Marco Lazzarino. A Micromechanical Switchable Hotspot for SERS Applications. *Applied Physics Letters*, 109(13):131108, September 2016.

Lars O Herrmann, Antonis Olziersky, Cynthia Gruber, Gabriel Puebla-Hellmann, Ute Drechsler, Tobias von Arx, Kouhsik Venkatesan, Lukas Novotny, and Emanuel Lörtscher. Fabrication of NEMS Actuated Plasmonic Antenna Platform for the Study of Optical Forces and Field Enhancements in Hotspots. In *Asia Communications and Photonics Conference 2016*. Optical Society of America, 2016.

Brian J. Roxworthy and Vladimir A. Aksyuk. Nanomechanical Motion Transduction with a Scalable Localized Gap Plasmon Architecture. *Nature Communications*, 7:13746, 2016.

Dalziel J. Wilson, Cindy A. Regal, Scott B. Papp, and H. J. Kimble. Cavity Optomechanics with Stoichiometric SiN Films. *Physical Review Letters*, 103(20):207204, 2009.

Shoko Yamada, Silvan Schmid, Tom Larsen, Ole Hansen, and Anja Boisen. Photothermal Infrared Spectroscopy of Airborne Samples with Mechanical String Resonators. *Analytical Chemistry*, 85(21):10531–10535, 2013.

Silvan Schmid, Tolga Bagci, Emil Zeuthen, Jacob M. Taylor, Patrick K. Herring, Maja C. Cassidy, Charles M. Marcus, Luis Guillermo Villanueva, Bartolo Amato, Anja Boisen, Yong Cheol Shin, Jing Kong, Anders S. Sørensen, Koji Usami, and Eugene S. Polzik. Single-Layer Graphene on Silicon Nitride Micromembrane Resonators. *Journal of Applied Physics*, 115(5), 2014.

Emanuel Gavartin, Pierre Verlot, and Tobias J. Kippenberg. A Hybrid On-Chip Optomechanical Transducer for Ultra-sensitive Force Measurements. *Nature Nanotechnology*, 7(8):509–514, 2012.

Tom Larsen, Silvan Schmid, Luis Guillermo Villanueva, and Anja Boisen. Photothermal Analysis of Individual Nanoparticulate Samples Using Micromechanical Resonators. *ACS Nano*, 7(7):6188–6193, July 2013.

Ron Lishitz and M.C. Cross. *Nonlinear Dynamics of Nanomechanical Resonators*. Wiley-VCH, 2010.

Otto Loebich. The Optical Properties of Gold. *Gold Bulletin*, 5(1):2–10, March 1972.

Olivier Brand, Isabelle Dufour, Stephen Heinrich, and Fabien Josse. Resonant MEMS: Fundamentals, Implementation and Applications. Wiley-Blackwell, 2015.
FIG. 1. (a) SEM Image of the opto-mechanical resonator, made of two SiN strings covered with electrically-connected gold electrodes. The width of the gap at the center of the strings is between 0.55 \( \mu \)m and 1.65 \( \mu \)m depending on the sample measured. (b) The experimental setup used for our optical measurements. The strings are placed in a vacuum chamber with a static magnetic field (200 mT), and an oscillating current is sent through one of the strings. This will create Lorentz forces that will excite the in-plane mode of the string, changing the width of the gap between the strings. A tunable Ti-Sapphire laser, focused on the center of the gap between the strings, is then used to detect the string vibration through the modulation of the laser reflection on the moving mirror. A waveplate and two linear polarizers are used to adjust the laser power and its polarisation. The sample is kept in a vacuum chamber with the neodymium magnets used to create the static magnetic field. A silicon avalanche photodetector (Si APD) is used to detect the reflected optical signal. Both the APD and the sample are connected to a lock-in amplifier used to send the electrical current through the SiN string and to visualize the resulting changes in the reflected laser optical power measured by the APD.
FIG. 2. (a) The mechanical resonance peak of the fundamental in-plane mode of one of the 100 μm long strings, as measured from the change in the reflected laser power when an alternating driving voltage is applied to the string. The resonance peak becomes strongly nonlinear for higher driving currents, which is typical of mechanical string resonators. However, there seems to be a maximal driving voltage (15 mV here) above which the shape and amplitude of the resonance peak no longer change significantly, maybe corresponding to the voltage where the gap between the strings is completely closed. (b) The electro-optical modulation of the reflected laser power as a function of time, when driven at a frequency close to the resonance peak maximum, for the three samples we measured. These samples have different string lengths and therefore different resonance frequencies and maximal driving voltages. For the 100 μm string, we have a quasi-sinusoidal signal and an optical modulation depth of 31 %. For the 300 μm and 500 μm strings, we are able to achieve an optical modulation depth of close to 100 % with a driving voltage below 1 mV, but the modulated signal is no longer quasi-sinusoidal.
FIG. 3. (a) SEM image of the opto-mechanical resonator with comb-drives actuators. The width of the gap at the center of the strings is 1.25 $\mu$m. (b) The electro-optical modulation of the reflected laser power as a function of time, when this resonator is driven at a frequency close to its resonance peak maximum, for different driving voltages. The optical modulation depth here is of 82.3 % for $V_{AC} = 250$ mV.