Tunable metasurface using thin film lithium-niobate in the telecom regime - Supplementary Material

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1. Fabry-Pérot and Fresnel model

The Fresnel reflection coefficient, r_{12}, from an interface between refractive indices n_1,n_2, where the wave is initially in the material with n_1 is given by:

$$r_{12} = \frac{n_1 - n_2}{n_1 + n_2} \qquad \text{(S1)}$$

And the transmission coefficient is given by:

$$t_{12} = \frac{2 \cdot n1}{n_1 + n_2} \qquad \text{(S2)}$$

To simplify the reflection calculation, we neglect the air/ITO interface. We then have three relevant layers: ITO ($n1 = 1.96$), LiNbO ($n_2 \approx 2.21$) and Chromium ($n_3 = 3.2120 + 3.3i$). The total reflectance of the structure is given as:

$$r = \frac{r_{12} + (r_{23}t_{12}t_{21} - r_{12}r_{21}r_{23}) \cdot \exp\left(\frac{i4\pi}{\lambda}n_2 d\right)}{1 - r_{21}r_{23}\exp\left(\frac{i4\pi}{\lambda}n_2 d\right)} \quad \text{(S3)}$$

Where $\mathrm{d} = 480\ \mathrm{nm}$ is the thickness of the LiNbO. the total reflectivity by wavelength is given below and shows a Fabry-Pérot resonance around 1.55 $\mu\mathrm{m}$.

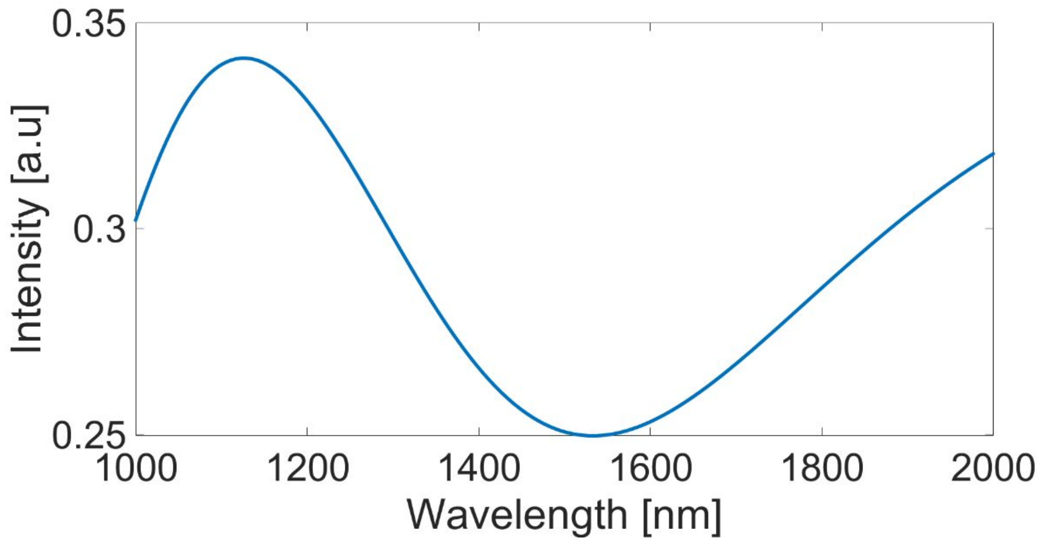

Fig S1. Reflected spectrum from the FP cavity showing a resonance at 1.55 $\mu\mathrm{m}$.

As can be seen, the FP effect is very broad and is thus less relevant for the tunability of the resonance.

2. Resonance dependency on structural design

To achieve a strong resonance matching with a strong confined electro-magnetic field in the LiNbO, an iterative optimization process was executed, simulating the reflected spectra for various values of the nano-cylinders diameter, thickness and the pitch between two nanoparticles. The strongest resonance at the wavelength $\lambda = 1.55\ \mu m$ was obtained with a 480 nm thickness of LiNbO, 200 nm cylinder diameter, 50 nm cylinder thickness and a periodicity of 830 nm. It is shown that the diameter and periodicity vary and distort the resonance significantly, while the thickness variation is weaker. An additional effect of the thickness is a diversion of the confined electro-magnetic wave to the Al-air interface from the desired Al-LiNbO interface.

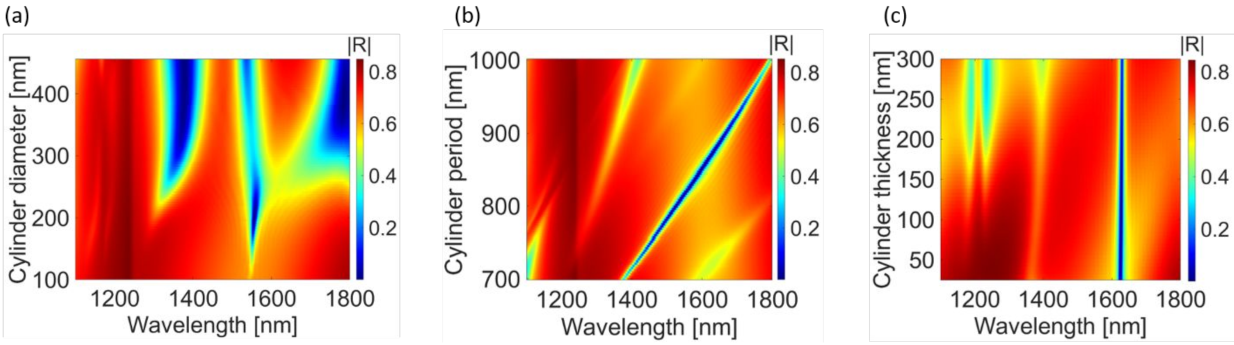

Fig S2. Simulations of the reflected spectrum dependency on the **(a)** nanoparticles diameter, **(b)** nanoparticles period and **(c)** nanoparticles thickness.

3. Effective refractive index of LiNbO

The spectrum reflectance was simulated as a propagating plane wave that incidents the structure in a perpendicular angle, which for a Z-cut LiNbO layer is the optical axis. Therefore, all the polarization components of the un-polarized beam are governed by the ordinary refractive index which for LiNbO is approximately $n_o \approx 2.21$. In an experimental design, the angle of incident has a variation which obligates a fraction of the beam to be governed by the extraordinary refractive index, which for LiNbO is $n_e \approx 1.14$. The effective refractive index will therefore be a weighed refractive index between these two values. simulations show that the effective refractive index that optimally fits our measurement is $n \approx 2.18$.

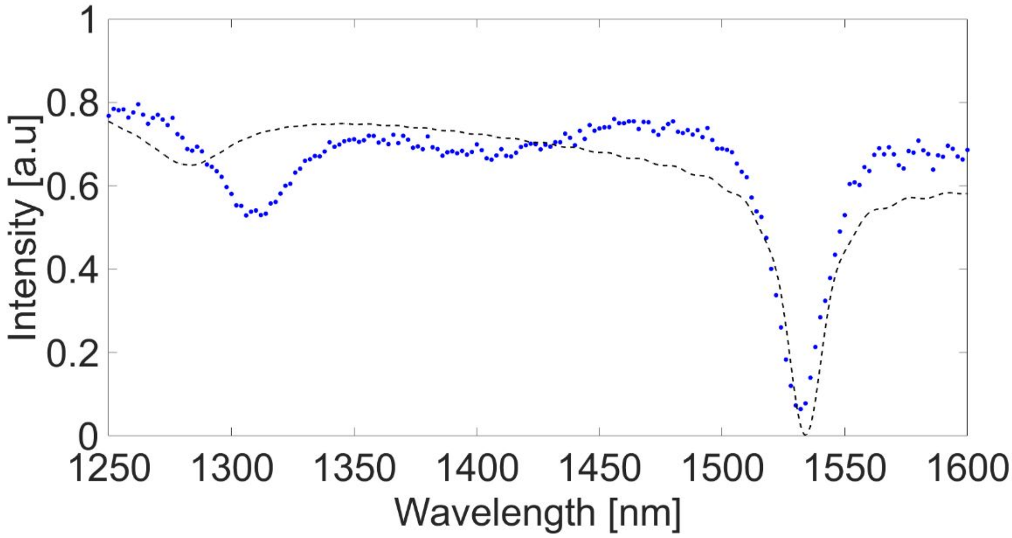

Fig S3. The measured spectrum of the device (blue dots) and the simulated spectrum (black dashed line) with an effective refractive index of $n = 2.18$ show a good agreement.

4. RC calculation

To estimate the resistance and capacitance of a Parallel plate capacitor with negligible current, we must take into consideration the complete system from the power generator to the structure. For the resistance, a BNC cable connects the Power Generator (PG) to a Voltage Amplifier (VA), both introducing a resistance of $50\ \Omega$ each. The VA is connected through an additional cable to a jumper wire which is connected to a soldered pin on a PCB mount. These elements exhibit several ohms of resistance and are therefore neglected. The PCB pad is wire bond (100Ω) to the pad on the structure. As the pad and the metasurface region are comparably wide, the main resistor in the system is the ITO wire connecting the pad to the metasurface. For our ITO, $\rho = 5.34 \cdot 10^{-6}\ [\Omega \cdot m]$, $h = 200\ [nm]$, $w = 10\ [\mu m]$, $l = 0.3\ [cm]$, where ρ is the ITO resistivity, h,w,l are the wire thickness, width and length, respectively. The total resistance of the ITO wires is $R = \frac{\rho l}{hw} = 8\ k\Omega$. The total resistance is approximately R= 8.25 $k\Omega$. To calculate the capacitance, following the bottom gold layer that sprawl over the entire region, the metasurface, pad and wires contribute to the capacitance. For a metasurface region of $A_m = 130X130\ \mu m^2$, a pad region of $A_p = 500X500\ \mu m^2$, and wires region of $A_w = 30000\ \mu m^2$, LiNbO width of $d = 480\ nm$, and permittivity of $\epsilon_r = 4.89$, the capacitance results in $C = \frac{\epsilon A}{d} \approx 25\ pF$. These results derive the 3dB cut-off frequency to by $f_{3dB} = \frac{1}{2\pi RC} = 781\ KHz$.

We denote that by replacing the ITO wires by gold wires where $\rho_{gold} = 2.44 \cdot 10^{-8}\ [\Omega \cdot m]$, the total resistance drops to $R\ \approx 200\ \Omega$. By applying voltage through probes instead of fabricated wires and pads the capacitance region will include only the metasurface and the capacitance results in $C = 1.5\ pF$. Using these simple adjustments we can reduce the resistance by 40 and the capacitance by 16 resulting in a cut-off frequency of $f_{3dB} = 520\ MHz$. Further optimization e.g. reducing the metasurface area and minimizing the resistance outside the sample could easily lead to a 3 dB cut-off frequency in the few GHz regime.

5. Input signal distortion

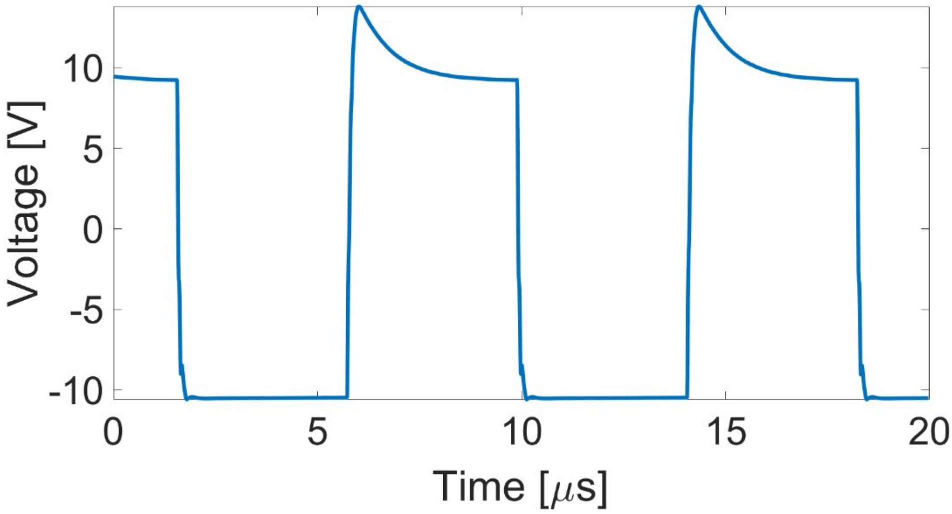

Fig S4. To measure bandwidth of the system we applied through the power generator a rectangular shape signal of 2V peak-to-peak. The signal was amplified using a voltage amplifier to 20V peak to peak. Due to the high voltage, the rectangular signal became distorted, resulting in an asymmetry in the measurements of the rise and fall time.