Ultrafast reconfigurability of circular dichroism from bound-states-in-the-continuum metasurfaces

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Abstract: We demonstrate a large and ultrafast reconfigurable circular dichroism arising from degenerate and tunable high-Q quasi-bound states-in-the-continuum resonances on a silicon metasurface using pump–probe spectroscopy.

1. Introduction

Dynamic reconfigurability of circular dichroism is of critical importance to several applications including holography, bio-sensing and free-space communication [1,2]. Quasi Bound state in the continuum (q-BIC) resonances [3,4] within metasurfaces have been used to control and enhance light-matter interaction due to their narrow line linewidth or high (Q) quality factor. The narrow linewidth of the resonances reduces the magnitude of the index change required to dynamically reconfigure the properties of the metasurface [5]. Here, we demonstrate for the first time, sub picosecond tuning of chiral light reflected from low-loss dielectric metasurfaces with degenerate high-Q resonances for left (LCP) and right (RCP) circularly polarized incident light using optically pumping (Drude free-carrier based index tuning). We observe a large change in circular dichroism >0.3 (or 20°) of the metasurface with the onset of the ultrafast optical pump.

2. Results and Discussion

We fabricate silicon metasurfaces on glass (Fig 1A); they consist of tall z-shaped fined resonators arranged in a triangular lattice and measure the reflection spectra as a function of the incident polarization. The reflection spectrum exhibits multiple high-Q resonance peaks at near infrared wavelengths (Fig 1B) with a degenerate pair of resonances overlapping at 1.22μm for chiral (LCP and RCP) incident light. These resonances disappear completely for linearly polarized light while the resonant line-shape form mirror images of each other under chiral (RCP and LCP incident light) illumination. These q-BIC resonances (Fig 1C) are characterized by helical waveguide (clockwise: RCP and counter-clockwise: LCP) modes travelling through the height of the resonators. The reflection spectra ($R\ vs\ \omega$) are fit with a resonant Fano equation- $R = \frac{\left(\frac{q\Gamma_{res}}{2}+\omega-\omega_{res}\right)^2}{\left(\frac{q\Gamma_{res}}{2}\right)^2+(\omega-\omega_{res})^2}$; where q, ω_{res} & Γ_{res} represent the Fano factor, resonant frequency and linewidth, respectively. We demonstrate that these are degenerate modes with the same linewidth ($Q_f = 181$) differing only by the sign of the Fano factor q : where RCP light has q = +4, and LCP light has q = -4, yielding a large spectral change in the circular dichroism (ΔCD ~ 0.8 or 44°) for this metasurface over a narrow (12.5nm) spectral bandwidth (Fig 1C). This metasurface design with high-Q degenerate resonances for oppositely polarized chiral illumination enables us to extract a near-unity change in circular dichroism with minimal absorption losses in a scalable semiconductor platform.

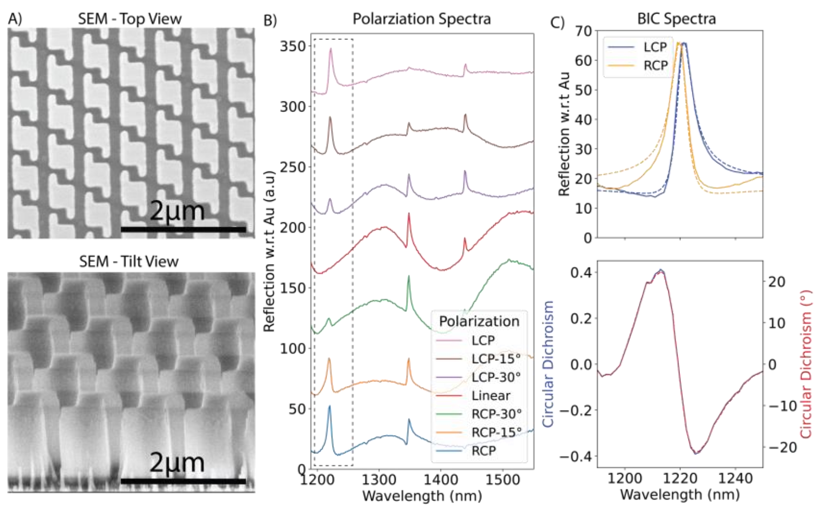

Figure 1 Chiral BIC Metasurfaces: A). Scanning Electron Microscopy (SEM) images of the fabricated silicon on glass metasurfaces: period = 700nm, resonator width = 280nm (square), fin length = 175nm, fin width = 80nm, height = 1.26μm. B) Reflection spectra of the metasurface as a function of the incident polarization. The dashed box shows the BIC resonance highlighted in panel C and tuned in figure 2. C) Reflection spectra (top panel) of the BIC resonances with model fits (dashed lines). Bottom panel shows the CD = (R_{RCP} -R_{LCP})/ (R_{RCP}+ R_{LCP}) plotted on absolute scale on the left axis and angle scale on the right axis (CD° = $\tan^{-1}$(CD)).

We leverage this q-BIC resonance combination to demonstrate a dynamic change in the CD through free-carrier based index tuning of the silicon metasurface, using optical pump (600nm)-probe (1200nm) spectroscopy. We generate the 1200nm, 260fs (pulse-width) probe beam using the idler of a Spirit NOPA (1MHz repetition rate) laser while the pump (600nm) is generated using frequency doubling in a BBO crystal from the 1200nm beam as shown in Figure 2A. When the optical pump is absorbed, it generates free carriers in the resonator which decreases the refractive index of Silicon leading to a blue shift in the resonant wavelength. The free carriers generated in the resonators relax with an exponential decay constant of 7ps (Fig 2B) over the entire spectral bandwidth of the probe pulse; this decay constant is consistent with previously measured values that has been assigned mostly to surface-recombination [6]. We demonstrate a pump power dependent dispersion of the resonances under LCP and RCP illumination as the peak in the differential (before and after T_0 – representing the temporal overlap between the pump and probe pulses) reflectivity plot (Fig 2B) blue shifts with increasing pump power. Thus, a larger spectral shift is observed for increased pump power resulting from a larger index change. It is also worth noting that with an increase in the pump power, the free carriers generated in the resonators start absorbing the probe beam and dampen the resonance, which results in a broader dip and shallower peak in the differential reflectivity plot. The change in the real part of the index results in a spectra peak shift while increased absorption from the free carriers results in resonance Q-factor reduction [6]. Altogether, the refractive index change in the resonator causes a large change in the CD spectra of the metasurface of 0.35 or 23° at 5mW (or ~60µJ/cm^2) pump power. The measured change in CD over a narrow spectral range is enabled by the high-Q degenerate BIC resonances is almost a factor 4X greater than previously reported dynamic CD changes [5] and additionally this also represents the largest change in CD per unit change in the index of the resonator.

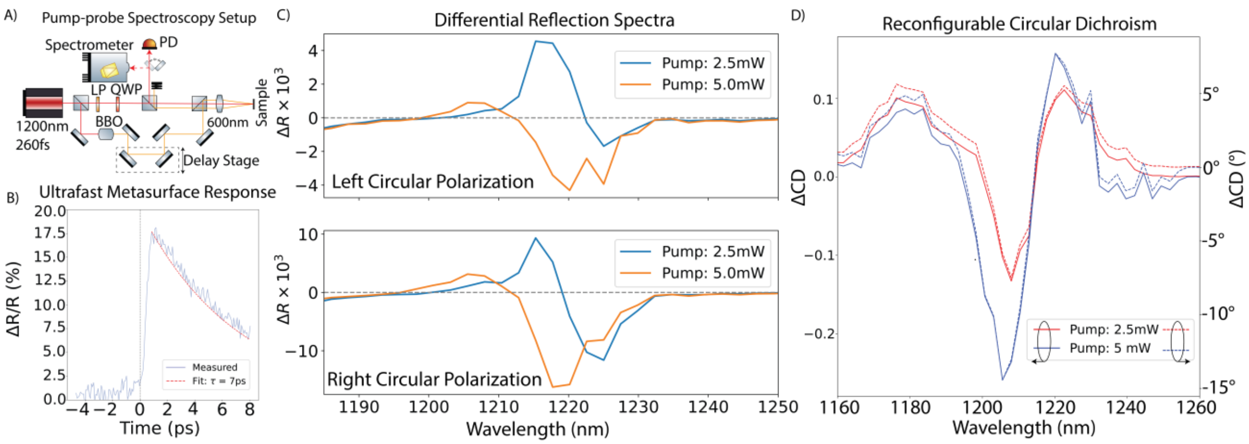

Figure 2: Ultrafast Reconfigurability: A) Pump (600nm) - Probe (1200nm) spectroscopy setup used to measure the dynamic response of the metasurfaces. B) The temporal response of the metasurface is measured in terms of percentage change in reflectivity to demonstrate a carrier decay time of 7ps (red dashed line) with an exponential fit. C) The differential reflectivity spectra ($R_{T>0} - R_{T<0}$) is plotted demonstrating the dynamic spectral shift in the BIC resonance for LCP (top) and RCP (bottom) incident probe pulse as a function of the pump power (blue – 2.5mW and orange- 5mW). D) Dynamic change in the CD spectra of the metasurface is plotted in absolute values (left axis, solid lines) and on the angle scale (right axis, dashed lines) for different pump powers (blue- 2.5mW and red -5mW).

In conclusion, we have demonstrated ultrafast tuning of circular dichroism from degenerate q-BIC resonances in Silicon metasurfaces using pump-probe spectroscopy. The optical pump leads to an index change based on Drude free carriers leading to sub-ps blue shift in the resonant wavelength (~20nm) of both LCP and RCP illumination. The resonant wavelength dispersion results in a shift in the CD spectra demonstrating 23° change over the 13nm spectral bandwidth. Thus, we demonstrate the potential of high-Q quasi-BIC resonances in silicon resonators enabling a new approach for engineering chiral light-matter interaction and dynamic polarization control at the sub-wavelength scale.

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3. References

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