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Authors
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Bandwidth-Engineered Ultra-Fast Time-Variant Metasurfaces

Ziwei Yang[1], Mingkai Liu[1], Daria Smirnova[1], Andrei Komar[1], Maxim Shcherbakov[2], Dragomir Neshev[1]

1. ARC Centre of Excellence for Transformative Meta-Optical Systems (TMOS), Dept. of Electronics Materials Engineering, Research School of Physics, Australian National University, ACT 2601, Australia.

2. Department of Electrical Engineering and Computer Science, University of California, Irvine, CA 92697, USA

Time-variant metasurfaces [1] have recently provided an ultra-fast approach to manipulating the optical response compared with conventional tunable approaches, like thermal and electric tuning. They allow for femtosecond scale switching by tuning under high-energy pumping sources. However, despite the recent advances in this field, the ability to precisely tailor the metasurface bandwidth with ultra-fast time response has not been carefully explored.

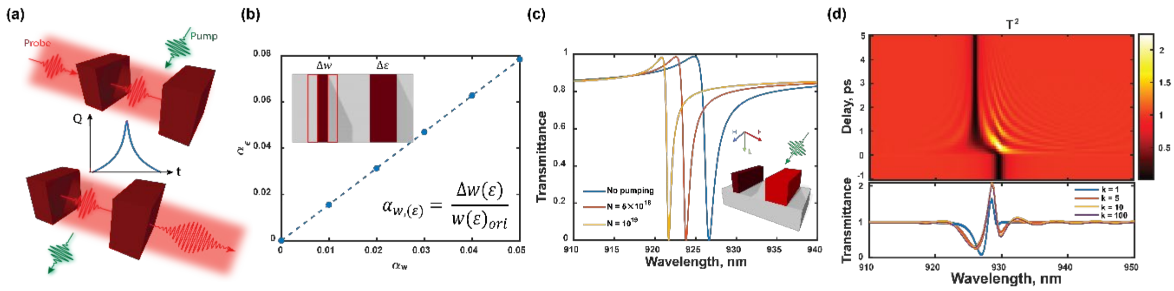

Fig. 1 (a) Schematic of Q-boosting time variant resonator. (b) Relationship of BIC resonance tuning between percentage of disbalance structure and permittivity change. (c) is simulated transmittance of time variant metasurface with one side grating pumping. Top figure of (d) is Q-boosting behaviour in transmittance at k = 10, bottom (d) shows the transmittance gain at 0 delay with different k value.

In this work, we present theoretically the optical response of the time-variant metasurface and its Q-boosting phenomenon [2,3]. The concept is presented schematically in Fig. 1 (a), where we show the manipulation of resonant bandwidth in a nano-resonator by external pumping. The probe pulse will be squeezed or extended in time domain when a short pump pulse stimulation changes the permittivity of the semiconductor resonator. Instead of the traditional bulky semiconductor resonator, the thickness of the metasurface is only several hundred nanometres. Therefore, the free carriers inside the semiconductor can be distributed uniformly, ensuring a homogeneous permittivity change. The inset of Fig. 1(b) demonstrates the unit cell of the metasurface. We artificially disbalance the symmetry of a semiconducting metasurface grating to generate a Bound state in the continuum (BIC) resonance, and the Q-factor of the resonance exponentially changes with a small perturbation when we open the resonance close to the BIC point. Fig. 1(b) depicts the compensation relationship between the width disbalance and the permittivity disbalance required to achieve the BIC point. This figure demonstrates how much permittivity change is needed to close the BIC resonance, which opened by the disbalanced width. The optical response of the metasurface is shown in Fig. 1(c), where the carrier density injection squeezes resonance's bandwidth. When we excite the metasurface by a femtosecond pulse, the carriers will be accumulated, and the Q-factor of the resonance will be increased rapidly on the femtosecond scale. In the top Fig. 1(d), we demonstrate the resonance shifting and the Q boosting based on pump-probe delay when the probe pulse touches the time boundary of permittivity change. Also, the transmission of different k value, the exponential coefficient of a Heaviside function describes bandwidth of a pump pulse, are shown at the bottom Fig. 1(d).

We amend our FDTD simulations with a temporal coupled mode theory (TCMT) to reveal the bandwidth switching, Fig. 1(d), and it gives a new degree to describe the time-variant phenomenon when the switching is faster than a resonance lifetime. The analytic solution of TCMT shows the same behaviour as the FDTD simulation. Therefore, the equation and parameters of TCMT can provide a deep insight into coupling and ultra-fast phenomena which are not covered by the numerical methods.

Overall, our results demonstrate **a novel way to engineer the time-bandwidth response of time-variant metasurfaces by balancing the geometric and dynamic asymmetries in the metasurface parameters**.

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