Microwave realization of multiresonant metasurfaces for achromatic pulse delay

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Abstract. We propose a microwave realization of a metasurface that can delay broadband pulses without distortion in reflection. In order to obtain large and broadband pulse delay, we harness the synergetic phase delay of five sharply-resonant meta-atoms. More specifically, three electric-LC and two split ring resonators, supporting electric and magnetic dipole resonances, respectively, are combined in a subwavelength unit cell. The resonances are spectrally interleaved and specifically designed to provide a spectrally-constant reflection amplitude and group delay according to the prescription in [ACS Photonics 5, 1101, 2018]. The designed metasurface is electrically ultrathin ($\lambda_0/19$), since it relies on resonant phase delay exclusively, instead of phase accumulation via propagation. We show delay of 700-MHz Gaussian pulses centred at 11 GHz by 1.9 ns, corresponding to approximately 21 carrier cycles. Our results highlight the practical potential of metasurfaces for broadband dispersion control applications.

1. Introduction
Metasurfaces, the two dimensional counterparts of metamaterials, promise to revolutionize electromagnetic wave control and replace conventional bulky components [1,2]. However, they have found limited use in broadband applications due to their resonant, narrowband nature. An approach that can increase the aggregate bandwidth is to combine multiple resonant meta-atoms in the unit cell. By properly designing the resonances, the respective phase delays stemming from each resonance (that are by themselves dispersive) can combine into an achromatic, spectrally-constant group delay that can be exploited for achromatic pulse delay [3] and wavefront manipulation [4] applications. The achieved group delay is enhanced with respect to that of the single resonance, due to the synergetic action of the resonance ensemble.

In this work, we demonstrate a microwave realization of a broadband time delay metasurface operating in reflection, by using five meta-atoms to implement five spectrally-interleaved sharp resonances (two magnetic and three electric), specifically designed according to the prescription in Ref. [3]. The designed metasurface is electrically ultrathin ($\lambda_0/19$), since it relies on resonant phase
delay exclusively, instead of phase accumulation via propagation. We show delay of broadband, 700-MHz Gaussian pulses centred at 11 GHz by 1.9 ns (21 times the carrier cycle $T_0=1/f_0$).

2. Results

The underlying concept of this work is shown in Fig. 1. A singly-resonant metasurface can be described by a homogenized Lorentzian electric surface conductivity $\sigma_{se} = i\kappa_e\omega/(\omega^2 - \omega_0^2 + i\Gamma_0\omega_0)$, where $\sigma_{se} = \eta\sigma_{se}/2$ is the dimensionless conductivity, $\omega_0$ the resonant frequency, $\kappa_e$ the coupling strength, and $\Gamma_e$ the dissipation. A sharp resonance results in a narrow bandwidth of high reflection, as shown in Fig. 1(a); at the same time the supplied group delay rolls off rapidly (the peak is obtained on resonance and can be calculated analytically: $\tau_g(\omega_0) = 1/[\pi(\kappa_e + \Gamma_e)]$. A crude approach to extend the metasurface bandwidth would be to make the resonance wider [Fig. 1(b)]. However, this decreases the supplied group delay considerably. An alternative option is to utilize multiple sharp resonances; then, we can harness the strong phase delay of the constituent resonances and at the same time obtain a broad aggregate bandwidth, extending in principle arbitrarily the delay-bandwidth limit. By using the prescription in Ref. [3], the decaying tails of the respective group delay contributions combine in a flat-top region with increased group delay. An example with five resonances is shown in Fig. 1(c). Such a metasurface can delay broadband pulses in reflection without distortion, as schematically shown in Fig. 1(d). Note that we have allowed for both electric and magnetic polarizability, in order to obtain control over unidirectional scattering; operation in reflection requires interleaved electric and magnetic resonances, whereas operation in transmission requires overlapped resonances. Scaling of the metasurface bandwidth for a larger number of resonances, $N$, is depicted in Fig. 1(e), (f), referring to the half-power bandwidth (HPBW) of the reflection amplitude, $BW_R^N$, and the bandwidth of the group delay, $BW_\tau^N$, measured at the 90% points, respectively. These quantities are normalized to the respective quantities for a single resonance, $BW_R^1$ and $BW_\tau^1$. As can be seen in Fig. 1(f) for example, the constant-group-delay bandwidth follows a linear dependence $BW_\tau^N \sim 0.8(BW_\tau^1)N$. The slope of 0.8 indicates the contribution of each resonance to the aggregate bandwidth.

Figure 1. Homogenized electric surface conductivity of an abstract metasurface with a sharp Lorentzian resonance. The group delay reaches 9.5$T_0$ but for a very narrow bandwidth that cannot accommodate real-world broadband signals. The gray shading denotes the bandwidth of high reflection amplitude. (b) The bandwidth can increase with a brighter (broader) resonance but at the expense of weak group delay. (c) Properly arranged multiple sharp resonances can provide a spectrally-constant reflection amplitude and group delay that can be used to delay broadband pulses without distortion. (e) Schematic illustration of pulse delay operation in
reflection. (e,f) Scaling of available bandwidth with number of resonances. (e) Half-power bandwidth (HPBW) of reflection amplitude, $BW_\text{HPBW}^N$, normalized to $BW_\text{HPBW}^1 = \bar{\kappa} + \Gamma_e$. (f) Group delay bandwidth measured at the 90% points, $BW_\text{GDBW}^N$, normalized to $BW_\text{GDBW}^1 = \bar{\kappa} + \Gamma_e$. The slope of the linear fit is 0.8 indicating the contribution of each resonance to the achieved aggregate bandwidth.

We now focus on the physical implementation of the scenario in Fig. 1(c) for the 10-GHz regime. We use the most straightforward strategy of one meta-atom per resonance. Electric-LC (ELC) and split-ring resonator (SRR) meta-atoms implement the electric and magnetic dipole resonances, respectively, as seen in the generic schematic of Fig. 2(a). A three-metallization-layer symmetric printed circuit board (PCB) is used; the patches of the SRRs reside in the top and bottom layers, whereas the ELCs in the middle metallization layer. Resorting to the theoretical recipe in Ref. [3], we require electric and magnetic resonances with a frequency spacing of 500 MHz, a dissipation coefficient of $\sim 35$ MHz, and a coupling strength of $320$ MHz. The resonances can be seen in the electric and magnetic surface conductivities depicted in Fig. 2(b). The conductivities have been retrieved by applying the expressions in Ref. [3] to plane-wave scattering coefficients obtained via full-wave simulations of a single unit cell in the periodic structure (periodic boundary conditions are applied at $x$- and $y$-boundaries). This specific combination of resonances, can theoretically provide a spectrally constant group delay of 2 ns over a 700-MHz bandwidth, while providing a high, flat reflection amplitude of $|r| = 0.8$. Indeed, the simulated response (full wave solution of Maxwell’s equations) depicted in Fig. 1(c) indicates a very good approximation of the targeted response with only minor ripples of the reflection amplitude and group delay inside the designed reflection band. Further details on the physical implementation (meta-atom dimensions and exact placement in unit cell, etc.) and an experimental verification of the proposed structure can be found in Ref. [5].

The spectrum of a 700-MHz Gaussian pulse is also included in Fig. 2(c) with a thick black line; the entire pulse bandwidth nicely fits inside the reflection band. The pulse delaying properties of the designed metasurface are demonstrated in Fig. 2(d). The output pulse is delayed by 1.9 ns ($\sim 21T_0$) without broadening nor distortion. The output peak intensity is $\sim 0.65$, since the amplitude reflection coefficient in Fig. 2(c) is $\sim 0.8$. For comparison, if a broad single resonance was utilized, as in Fig. 1(b), the pulse would be delayed by only 0.35 ns. Using five resonances we were able to gain approximately a five-fold improvement in the attained group delay. In addition, using a single resonance would lead to a pulse broadening of $\sim 10\%$, due to the group delay dispersion inside the pulse bandwidth [cf. Fig. 1(b)]; in contrast, pulse broadening in Fig. 1(d) is below 1%.

![Figure 2](image)
MHz Gaussian pulse in the temporal domain. The pulse is delayed by 1.9 ns (~21T₀) without distortion.

3. Conclusion

We have designed a microwave physical implementation of an achromatic metasurface that can delay broadband pulses in reflection. Our approach relies on fitting five sharply-resonant meta-atoms inside a subwavelength unit cell. The metasurface is electrically ultrathin (λ₀/19), since it relies exclusively on resonant phase delay. The proposed metasurface has been fabricated in the form of two boards (0.787-mm thick) made of Rogers RT/duriod 5880 (εᵣ = 2.2 and tan δ = 9 × 10⁻⁴ at 10 GHz). One board is implementing the top SRR metallization layer and the ELC meta-atoms and the second is implementing the bottom SRR metallization layer. The boards have been assembled with chip resistors [instead of plated through vias schematically depicted in Fig. 2(a)] to complete the electrical continuity of the SRR meta-atoms and measurements with horn antennas and a vector network analyzer have been performed [5]. Our work highlights the practical potential of metasurfaces for dispersion control applications that rely on large and broadband phase delays.

4. References

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