Time-modulated Computational Metasurfaces

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Material-based time-dependent systems endow flexible routes for designing a wide variety of active devices. Periodic dynamic modulation of material properties, in particular, brings an additional degree of freedom for obtaining unprecedented wave effects in various type of wave platforms [1]. Here, we explore the possibility to use time-modulated metasurfaces as spatial analog processors, by leveraging their capability to provide controlled frequency harmonic generations and parametric amplification effects. We demonstrate two examples: (i) we address the shortcoming of passive spatial analog integrators by exploiting parametric gain, and (ii) we engineer various frequency-conversion schemes to make reconfigurable logical gates with a fixed physical structure.

Among the various standard mathematical operations, integration plays an important role in signal processing, especially for optical communications. Optical integrators may be used for shaping optical pulses, as well as step or a flattop signals from standard optical Gaussian pulses. Moreover, optical integrators can potentially be used as basic building blocks in all-optical signal processing systems. So far, previously-proposed metamaterial-based analog optical integrators, which operate in the spatial domain, have been based on passive structures that do not work when fed by signals rich in low-spatial frequency contents. This property arises from the necessary truncation of low-frequency contents (DC components) of the input wave in the spatial Fourier domain, due to the passivity constraint. In fact, passive material platforms must possess a sub unitary transmittance, i.e. a limited-amplitude Transfer Function (TF) that is incompatible with the spatial integration operation with the TF of $1/(\mathrm{j}k_x)$ [2]. To solve this shortage, we need to employ gain to amplify the monochromatic input signal. One way to do so is to use a periodic temporal modulation of the physical properties of the medium, pumping the wave by gain of parametric nature. By employing surface impedance model, we design and demonstrate such possibility in a simple stable parametrically driven metasurface, achieving both the amplitude and phase required by the ideal spatial integration's TF.

In addition, combinatory logic circuits are at the heart of all computers. Optical logic gates, for example based on silicon-based technologies, are essential for the further development of optical analog processors, optical information processing, and secured wireless communications. Therefore, there exists a strong interest to design optical logic gates with complete logic functionality and compact dimensions [3]. Here, we exploit time-modulated structures to design a meta-perceptron neural network capable of performing tunable logical operations such as XOR, AND, and OR. By leveraging the frequency conversions induced by the time modulation, we design reconfigurable logical gates with a fixed geometry. By introducing a time-modulated component in a metasurface in the form of a time-varying capacitor ($\mathrm{C} = \mathrm{C}_0 + \mathrm{C}_\mathrm{m} \cos(\omega \mathrm{t} + \varphi)$), and tuning the modulation depth C_m and phase φ, we can realize different types of logical gates. The two inputs of the perceptron metasurface are carried by monochromatic waves with central frequencies of ω_1 and ω_2. By setting the time-modulation frequency to the low value $\omega_m = |\omega_1 - \omega_2|/2$, and properly tuning the C_m and φ coefficients, an output signal can be defined at the intermodulation frequency $\omega_{out} = (\omega_1 + \omega_2)/2$, and various logical operations can be induced. Such time-varying wave-based computing systems can set the path for future developments of applications in optical neural networks and parallel signal processing.

References

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