Reflective metasurfaces based on extended Babinet's relations

Takayoshi Fujikawa and Toshihiro Nakanishi*
Department of Electronic Science and Engineering, Kyoto University, Kyoto, Japan
**E-mail:t-naka@kuee.kyoto-u.ac.jp*

Babinet's principle states that there is a relationship between the scattering fields from a planar metallic structure and those from its complementary structure, which is obtained by swapping metallic parts and insulating parts[1]. It has been widely applied to the design of single-layer transmissive metasurfaces to control the transmitted waves[2]. However, it is well known that single-layer metasurfaces are inherently inefficient due to reflection loss. In contrast, reflective metasurfaces composed of planar metallic structures and a reflective mirror can efficiently manipulate electromagnetic waves, because all energy is reflected owing to the presence of the mirror.

We have extended the conventional Babinet's relations for transmissive metasurfaces and found that similar relations can be derived for reflective metasurfaces under specific conditions[3]. We consider a reflective metasurface as shown in Fig. 1(a), which is composed of a reflective mirror and a substrate embedding self-complementary metallic structures. If the refractive index of the substrate is $n = 2$ and the thickness is set to be half the operating wavelength, the reflection coefficients for TE waves $\tilde{r}_{\rm TE}$ and TM waves $\tilde{r}_{\rm TM}$ satisfy $\tilde{r}_{\rm TE} + \tilde{r}_{\rm TM} = 0$, which can be regarded as an extended Babinet's relation. We numerically calculated the reflection coefficients for three metasurfaces (A, B, and C) with different design parameters under ideal conditions without Joule loss in the metal. The obtained reflection coefficients on a complex plane are shown in Fig. 1(b). It can be confirmed that $\tilde{r}_{\rm TE} + \tilde{r}_{\rm TM} = 0$ for all three cases, which means that the reflective metasurface embedding self-complementary structures always works as a half-wave plate. This property can be applied to simultaneous control of reflection angle and polarization by arranging various self-complementary structures to realize phase gradients as shown in Fig. 1(c).

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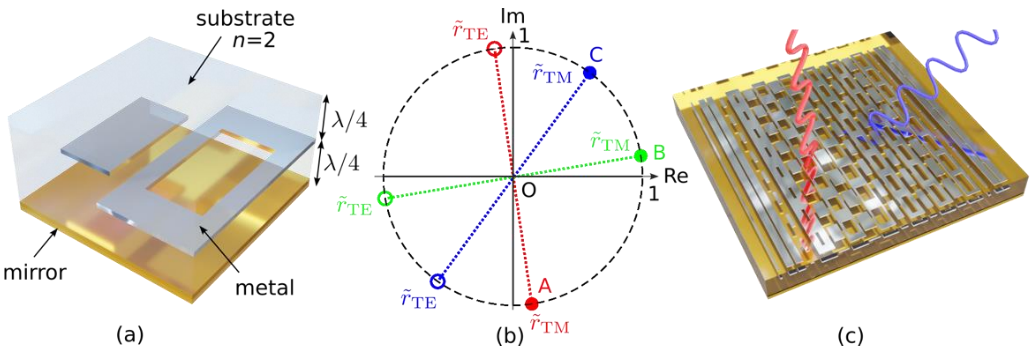

Fig. 1 (a) Design of reflective metasurface satisfying extended Babinet's relation. (b) Calculated reflection coefficients on a complex plane. (c) Schematic diagram of reflective metasurface for simultaneous control of reflection angle and polarization.

References

1. Y. Nakata, Y. Urade, T. Nakanishi, and M. Kitano, Phys. Rev B. **88**, 205138 (2013).
2. Y. Urade, Y. Nakata, T. Nakanishi, and M. Kitano, Phys. Rev. Lett. **114**, 237401 (2015). Y. Nakata, Y. Urade, K. Okimura, T. Nakanishi, F. Miyamaru, M. W. Takeda, and M. Kitano, Phys. Rev. Appl. **6**, 044022 (2016). Y. Nakata, K. Fukawa, T. Nakanishi, Y. Urade, K. Okimura, and F. Miyamaru, Phys. Rev. Appl. **11**, 044008 (2019).
3. T. Fujikawa and T. Nakanishi, Phys. Rev. Appl. **22**, 034002 (2024).