DOI: https://doi.org/10.15407/rpra27.03.181
UDC 537.876

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# INTENSITY CONTROLLED, NONSPECULAR RESONANT BACK REFLECTION OF LIGHT

***Subject and Purpose.*** *Theoretical demonstration of controllable features of a non-conventional resonant back reflection of light, realizable with the aid of a structured silicon-on-metal covering.*

***Methods and Methodology.*** *The investigation has been performed through a full-wave numerical simulation in a finite-element technique.*

***Results.*** *The nonlinear optical properties of a planar structure, involving a set of silicon disks disposed periodically on a silver substrate, have been studied in the Littrow scenario of wave reflection. The structure manifests a bistable resonant reflectivity property. The magnitudes of both specular and back reflection ratios can be controlled by means of varying the incident light intensity.*

***Conclusions.*** *An array of identical silicon disks, placed in a periodic order on a silver substrate, can be employed as an efficiently excitable and tunable nonlinear resonant reflective structure implementing Littrow's non-specular diffraction scenario. As has been found, the effect of nonlinear response from the silicon disks can be used for implementing a regimen of bistable back reflection, controllable by means of varying the incident wave's intensity. The nonlinear tunability of the silicon-on-silver structure does promise extensions of the operation area of classical metamaterials of sub-wavelength scale sizes as it offers new applications for the effects of light-matter interaction.*

***Keywords:*** *metasurface, non-specular reflection, Littrow's scenario, nonlinear tunability, bistability, numerical simulation.*

## Introduction

The plane metallic mirror is the simplest optical device that has been used since antiquity [1]. A remarkable and extremely useful feature of the mirror is its ability to sharply change the direction of light rays and, in the case of normal incidence, return the light back over a wide spectral bandwidth. Today's photonics requires mirrors with special reflective properties, like, in particular, wavelength-dependent selectivity with regard to both the electromagnetic field intensity and phase. The phase variations along the reflecting surface can be specially adapted in order to control, redirect and concentrate the intensity of light.

Citation: Prosvirnin, S.L., Khardikov, V.V., Yachin, V.V., Plakhtii, V.A. and Sydorchuk, N.V., 2022. Intensity controlled, nonspecular resonant back reflection of light. *Radio Physics and Radio Astronomy*, **27**(3), pp. 181—187. https://doi.org/10.15407/rpra27.03.181
Цитування: Просвірнін С.Л., Хардіков В.В., Ячин В.В., Плахтій В.А., Сидорчук Н.В. Зворотне резонансне недзеркальне відбиття світла, кероване його інтенсивністю. *Радіофізика і радіоастрономія*. 2022. Т. 27. № 3. С. 181—187. https://doi.org/10.15407/rpra27.03.181

Metasurfaces open prospects for creating special reflectors with extraordinary properties [2]. The wavelength-selective properties of mirrors are necessary for designing precise sensors [3–5], in particular, those working with biological material [6]. Another aspect of resonant mirror applications relates to quantum-mechanical systems possessing different energy states, which are placed in areas of high field intensity near a reflecting surface. In this case, the challenge is to obtain either a maximum radiation intensity or an extra absorption. In the light of these problems, the appliances that might seem attractive for practical applications owing to their promising features are, along with classical metasurfaces, resonant arrays capable of radiating light waves within just one or a few diffraction orders along with the principal one [7, 8]. Modern optical technologies present an opportunity of producing non-specularly and selectively reflecting metasurfaces. A reflecting metasurface is usually a planar dual-periodic, sub-wavelength patterned metal-dielectric or all-dielectric layer placed on a metal substrate [9]. The thickness of a metasurface layer usually is very small compared with the electromagnetic wavelength in free space. However, the periodically structured surface provides conditions for excitation of a variety of types of resonances. A spectacular metasurface response manifests itself through such effects as resonance reflection and absorption [10], enhancement of electromagnetic radiation in a laser medium [11], implementation of exotic boundary values for the electromagnetic field, which may be the same as on the surface of an artificial magnetic wall [12], or else confinement of an intense electromagnetic field inside the structure [13].

Among the great many important electromagnetic properties, the ability of planar periodic structures to reflect an incident wave in a preferred non-specular direction is extremely attractive for applications in photonics [2, 9]. The early research projects on the subject date back to 1970s, being initially related to single-periodic reflective gratings aimed at suppressing unwanted reflection of microwave radiation [14–16]. In laser technology of optical electronics, inclined echelette grating mirrors were used to reflect light in the direction strictly opposite to the direction of arrival of the incident wave. The corresponding scenario of diffraction by a structure periodic in one direction is known as the Littrow scheme [17, 18] or an autocollimation regime. Another practically important diffraction scenario is when the obliquely incident wave is reflected in the direction normal to the metasurface. In particular, it is of interest for the design of quasi-optical pulsed power compressing devices [19].

As is known, in a particular diffraction scenario the propagation directions of diffraction orders depend on the geometry and relative size of the unit cell in the periodic metasurface with respect to the wavelength, as well as on the direction of the incident electromagnetic wave. On the other hand, the distribution of power between diffraction orders is determined only by resonance properties of the meta-atoms making up the periodic structure, and the amount of their coupling. Therefore, a change in the resonance properties of the meta-atoms opens up a possibility of switching the structure's reflectivity between the specular and non-specular reflection modes.

For changing the properties of meta-atoms, one of opportunities is to use materials in which polarizability depends upon intensity of the applied electromagnetic field [20]. In this case, switching between the modes of specular or non-specular reflection of light is achieved by changing the intensity of the incident wave. In particular, the optical Kerr effect is defined as an intensity dependent refractive index $n = n_0 + n_2 I$ where $I$ is the intensity of the optical field, $n_0$ the linear refractive index in the low light intensity regime, and $n_2$ the nonlinear refractive index.

The optical Kerr effect is a third-order effect which can lead to optical bistability of the structure's response. The phenomenon can underlie the design of devices like the toggle switch. Third order nonlinear optical properties are inherent to a variety of media (both centrosymmetric and noncentrosymmetric), in particular silicon which is the most used medium of photonics [21].

In this paper we suggest a first theoretical demonstration of controllable features of the uncommon resonant retroreflection regime, realizable with a patterned silicon-on-metal structure. The regime is associated with excitation of one additional diffraction order in addition to the main partial wave. The magnitude of the non-specular-to-specular reflection ratio can be controlled through varying the incident wave intensity. To provide for non-specular reflection from any direction of incidence, we have proposed an array of silicon disks with Mie-resonant inclusions. The array demonstrates a specific symmetry of field distribution [22], useful for mobile communications antennas.

We have so far assumed the electromagnetic field intensities at combination frequencies to be negligible, thus considering the fields as monochromatic. The grounds for such an approach is the use of resonant elements on the metasurface. The research work has been conducted as a full-wave numerical simulation in a finite-element technique.

## 1. Problem formulation

We have considered reflection of the plane electromagnetic wave,

$$\vec{E}^i = \vec{e}^{\,i} E \exp(-i\vec{k}^i \vec{r}),$$

by a dual-periodic reflecting structure placed in free space and parallel to the *xy*-plane (see Fig. 1). Here, $\vec{e}^{\,i}$ stands for a unit polarization vector; $E$ is the electric field strength in the incident wave, and

$$\vec{k}^i = \vec{e}_x k \sin\theta_i \cos\varphi_i + \vec{e}_y k \sin\theta_i \sin\varphi_i - \vec{e}_z k \cos\theta_i$$

is the wave vector, with $\varphi_i$ and $\theta_i$ denoting, respectively, the azimuth and the polar angle for the direction of incidence. Next, $k = \omega / c = 2\pi/\lambda$; the vectors $\vec{e}_x$, $\vec{e}_y$ and $\vec{e}_z$ are unit vectors along the axes *Ox*, *Oy* and *Oz* in the frame of reference.

In the region $z > 0$, the field is a superposition of the incident wave's field and those of partially diffracted waves that travel away from the structure and along its surface,

$$\vec{E} = \vec{E}^i + \sum_{m,n=-\infty}^{\infty} \vec{a}_{mn} \exp\left(-\vec{k}_{mn}\vec{r}\right), \quad z > 0,$$

with $\vec{a}_{mn}$ and $\vec{k}_{mn} = \vec{g}_{mn} + \vec{e}_z \gamma_{mn}$ being, respectively, vectorial amplitudes and wave vectors of the partial waves making up the reflected field. Next,

$$\vec{g}_{mn} = \vec{e}_x \left( k_x^i + \frac{2\pi m}{d} \right) + \vec{e}_y \left( k_y^i + \frac{2\pi n}{d} \right)$$

is a projection of the wave vector belonging to a Floquet harmonic within the *xOy* plane, and

$$\gamma_{mn} = \sqrt{k^2 - g_{mn}^2}, \quad (\mathrm{Re}\,\gamma_{mn} \ge 0, \mathrm{Im}\,\gamma_{mn} \le 0)$$

is the wave vector component along the *Oz*-axis.

Each spatial harmonic having a nonzero wave vector's real component $\gamma_{mn}$ corresponds to one of the plane waves that transfer energy from the plane of the array to free space. The ($m = 0$, $n = 0$) spatial harmonic is a plane wave propagating along the direction of specular reflection for the incident wave. Thus, the propagation directions of spatial harmonics or diffraction orders of the reflected field are defined by pitches of the array, and wavelength and direction of the incident wave. However, the intensity distribution of the spatial harmonics in the spectrum depends on scattering properties of the structure meta-atoms.

For the sake of simplicity and brevity we have further considered the case $\varphi_i = 0$. The incident wave is supposed to possess a *TE*-polarization, *i.e.* $\vec{e}^{\,i} = \vec{e}_y$.

It may prove convenient to introduce a normalized frequency defined as $\kappa = d/\lambda$. The equation $\gamma_{mn}(\kappa) = 0$ is that for the diffraction order cutoff frequencies $\kappa_{mn}$. If a normalized frequency is lower than $\kappa_{-10} = (1 + \sin\theta_i)^{-1}$, then there is just one specular ray traced away from the metasurface. The cutoff frequency of the diffraction order $(-2, 0)$ is $\kappa_{-20} = 2(1 + \sin\theta_i)^{-1}$. In the frequency band ($\kappa_{-10}$, $\kappa_{-20}$) the reflected far field consists of two rays which are diffraction orders $(0,0)$ and $(-1,0)$.

As can be easily seen, the diffraction order $(-1,0)$ existing at the normalized frequency $\kappa = (2\sin\theta_i)^{-1}$, propagates in a direction strictly opposite to that of the incident wave [18].

When choosing resonant elements for the metasurface, preference was given to silicon disks. Silicon had been proposed as the dielectric material most frequently used in photonics. The resonant features of a single dielectric disk located in free space or on a dielectric substrate have been well known [23]. Planar arrays of disks have also been studied in detail, for the case where the unit cell is smaller than the wavelength [13]. The attractive opportunities offered by dielectric disks on a metal substrate for such applications as antenna elements for mobile communication devices were discussed in paper [24].

## 2. Results of simulation and analysis

The silicon disks of the array are assumed to have been placed periodically over a thick plane substrate of silver (see Fig. 1). The array's period $d$ is equal

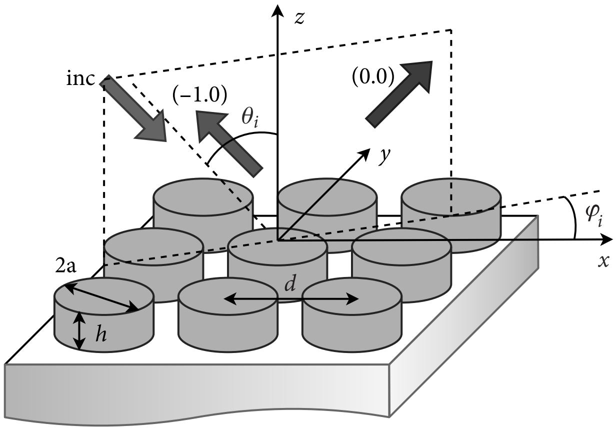


***Fig. 1.*** Schematic of the dual-periodic planar reflective structure under study. The incident ray (red arrow), as well as the specular- and the back-reflected ones (the blue and the green arrows, respectively) all lie within the plane of incidence (represented by the dashed parallelogram)

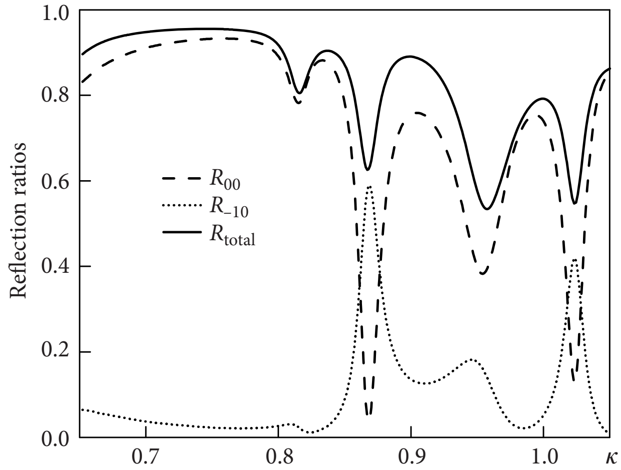


***Fig. 2.*** Reflection ratios as functions of the normalized frequency (linear regime). The approximate normalized frequency of 0.872 corresponding to the auto-collimation diffraction scenario is marked by a dashed vertical line

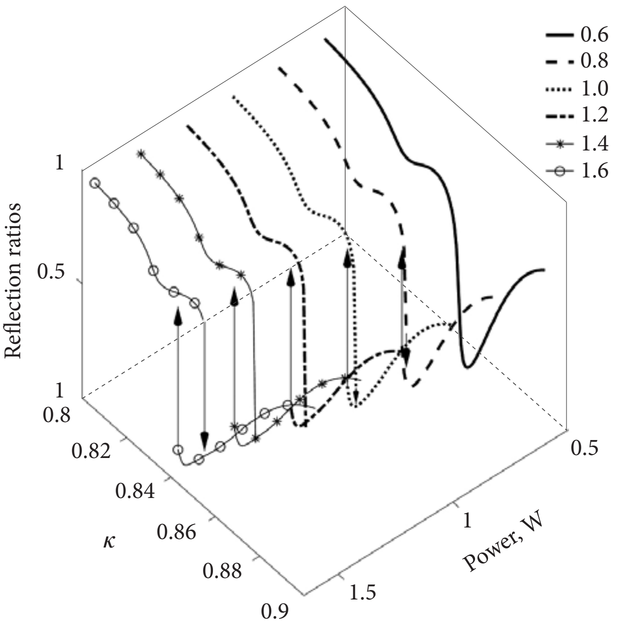


***Fig. 3.*** Specular reflection ratio, $R_{00}$, in dependence on the normalized frequency and the incident wave's per unit cell power at the reflect-array

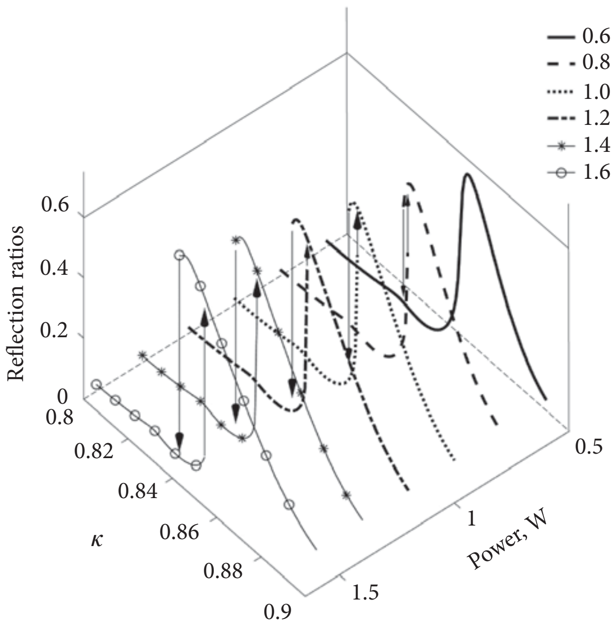


***Fig. 4.*** Back reflection ratio, $R_{-10}$, in dependence on the normalized frequency and the incident wave's per unit cell power at the reflect-array

to 750 nm. The disk radius is $a$ = 130 nm. The disk thickness is $h$ = 130 nm. The linear and nonlinear refractive indexes of silicon are approximated to as described in papers [25, 26, 27]. In particular, at frequencies close to the frequency of back reflection, they are $n_0 = 3.48$ and $n_2 = 10^{-18}$ m$^2$/W, respectively. These values generally correspond to those commonly used to study properties of nonlinear silicon metasurfaces [28]. The substrate thickness is assumed to be large enough for preventing penetration of the light field through the substrate. The refractive index of silver has been quoted from paper [29]. The angle of incidence is assumed to be $\theta_i = 35$ deg. This choice of the structure parameters gives us an opportunity to study the resonant diffraction efficiency of the specular-reflected wave and of the (–1,0) diffraction order propagating in an opposite direction to the incident wave.

In the linear regime the reflect-array designed demonstrates a strong resonant response at a frequency that is close to the frequency of the auto-collimation diffraction scenario resulting in excitation of an intense (−1,0) diffraction order. Fig. 2 presents the frequency dependence of the power reflection ratio, that is a measure of the amount of optical power reflected into a specific direction, compared with the power incident onto the reflecting object.

Note, that all calculations of the metasurface reflectance in linear and nonlinear modes was performed using the finite element method solver in COMSOL Multiphysics in the frequency domain. In the nonlinear mode, the variable parameter of the Comsol model was the incident wave intensity instead of the frequency.

The designed structure manifests a sharp resonant excitation of the (−1,0) diffraction order, owing to its adjustment to Mie's resonances of the silicon disk elements. The resonant mode is close to the $TE_{01\delta}$ resonance of a finite-length dielectric cylinder in free space.

The magnitude of resonant conversion of the specular ray intensity into the intensity of the back reflected ray depends on dissipative properties of the reflect-array. Proceeding from a non-dissipative theoretical model of the reflecting structure, we have shown a complete transfer of the incident wave's intensity into such of the backscattered wave (see [30]). The power dissipated by the array can be expressed in terms of the absorption index $A = 1 - R_{\text{total}}$ (see Fig. 2).

Simulation results concerning frequency dependences of the array's reflection ratios are presented in Figs. 3 and 4 versus the incident wave's power per unit cell of the array. We observed bistable reflection properties of the array in cases where the power was in excess of some value. Our estimate for the threshold power to give rise to reflection bistability is about 0.7 W.

Under bistability conditions the value of the reflection ratio at each power level depends on whether the bistable state has resulted from an up or down transition in frequency. With an increase in the intensity of the incident wave, the frequency zone of bistability expands and shifts toward lower frequencies. The frequency dependences of reflection ratios represent hysteresis loops. Within the frequency range of bistability the value of a reflection ratio depends on the kind of the trajectory to reach the bistable state.

## Conclusion

Summarizing the results, we can state that a set of identical silicon disks, dispozed periodically on a silver substrate can be used as an efficiently excitable and tunable resonant, nonlinear dielectric-metal hybrid reflect-array operated in the Littrow non-specular diffraction scenario. As has been found, the nonlinear response of the silicon disks is a property suitable for realizing a bistable back reflection regimen, controllable through variation of the incident wave's intensity. The nonlinear tunability of the silicon-on-silver structure is a promising feature for extending the operation area of classical sub-wavelength metamaterials as it provides new opportunities for light-matter interaction applications.

## Acknowledgments

*The support from the National Research Foundation of Ukraine (grant No 2020.02/0218) and the National Academy of Sciences is gratefully acknowledged.*

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*Received 09.05.2022*

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ЗВОРОТНЕ РЕЗОНАНСНЕ НЕДЗЕРКАЛЬНЕ
ВІДБИТТЯ СВІТЛА, КЕРОВАНЕ ЙОГО ІНТЕНСИВНІСТЮ

**Предмет і мета роботи.** Теоретична демонстрація контрольованих особливостей незвичайного резонансного режиму зворотного відбиття світла, що може бути реалізованим за допомогою структурованого покриття з кремнію на металі.

**Методи і методологія.** Дослідження виконано методом скінченних елементів та повнохвильовим чисельним комп'ютерним моделюванням.

**Результати.** Нелінійні оптичні характеристики плоскої структури, що складається з кремнієвих дисків, періодично розміщених на срібній підкладці, було досліджено за сценарієм відбиття Літтроу. Структура проявляє бістабільну резонансну відбивну здатність. Значення коефіцієнтів як дзеркального, так і зворотного відбиття можна налаштувати, змінюючи інтенсивність світла, що падає.

**Висновок.** Решітка з ідентичних кремнієвих дисків, періодично розміщених на срібній підкладці, може бути використана як ефективно збуджувана й регульована резонансна нелінійна відбиваюча структура у сценарії недзеркальної дифракції Літтроу. Виявлено, що нелінійний відгук кремнієвих дисків може бути використаний для реалізації бістабільного зворотного відбиття, котрим можна керувати шляхом зміни інтенсивності хвилі, що падає. Можливість нелінійного налаштування структури «кремній на сріблі» є перспективою для розширення робочої області класичних субхвильових метаматеріалів, змогу застосування ефектів взаємодії світло-матерія.

***Ключові слова:*** *метаповерхня, недзеркальне відбиття, сценарій Літтроу, нелінійна перестроюваність, бістабільність, чисельне моделювання.*