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Ultrahigh Contrast One-Way Optical Transmission Through a Subwavelength Slit

Enes Battal · Taha Alper Yogurt · Ali Kemal Okyay

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Abstract We computationally demonstrate one-way optical transmission characteristics of a subwavelength slit. We comparatively study the effect in single layer and double layer metallic corrugations. We also investigate the effect of a dielectric spacer layer between double corrugations to control the volumetric coupling of plasmon and optical modes. We computationally show unidirectional transmission behavior with an ultrahigh contrast ratio of 53.4 dB at λ=1.56 μm. Volumetric coupling efficiency through the nanoslit strongly depends on the efficient excitation of both the surface plasmon resonance and metal–insulator–metal waveguide modes. We show that the behavior is tunable in a wide spectral range.

Keywords All-optical devices · Coupled resonators · Gratings · Surface plasmons · Waveguides

Realization of unidirectional optical transmission is gathering great attention due to potential applications in integrated photonic circuits, optical interconnects, and optical and quantum computation [1]. One-way transmission characteristics are reported with nonlinear materials [2], photonic crystal fibers [3], left-handed periodic structures [4], photonic bandgap liquid-crystal hetero-junctions [5], magneto-optical materials [6], and quantum dots [7]. Recent reports observe one-way transmission behavior in the absence of nonlinear or anisotropic materials [1, 8–11]. Lockyear et al. [8] showed that it is possible to implement one-way transmission devices operating at the microwave frequencies using asymmetric rectangular gratings. In a double layer asymmetric grating structure, the transmission of one direction is improved by a resonant diffraction grating while the periodicity of the opposite orientation sustains only higher order modes [8]. Utilizing a double layer diffraction grating structure, Zen et al. [9] demonstrated that contrast ratios above 100 can be achieved.

Excitation of surface plasmon resonances by metallic gratings can be used to achieve enhanced transmission [12]. One-way transmission devices operating at telecommunication standard wavelengths have been realized exploiting plasmonic modes including the use of tunable plasmon resonances obtained on rectangular metallic gratings coated with nonlinear materials [13], asymmetric plasmonic gratings integrated in slot waveguides [14], and asymmetric rectangular diffraction gratings [1]. It was shown that transmission through subwavelength apertures can be enhanced by metallic gratings at the illuminated side of a subwavelength aperture which enables the coupling of surface plasmon modes with the aperture [15]. Moreover, both theoretical [10] and experimental [11] demonstrations of one-way transmission characteristics of asymmetric rectangular gratings coupled with a subwavelength aperture have been accomplished at microwave frequencies.

In this paper, we present the design and analysis of a one-way transmission device operating at the telecommunication standard wavelengths with an ultrahigh contrast ratio. Our design achieves strong unidirectional characteristics by exploiting the one-way transmission property of double layer gratings coupled with the extraordinary transmission through a subwavelength slit. We also investigate the effect of the resonant coupling of the modes of the front-side and back-side diffraction gratings on one-way transmission characteristics. We demonstrate that by controlling the coupling between the gratings with a separating dielectric layer, an ultrahigh contrast ratio can be achieved.

E. Battal (✉) · T. A. Yogurt · A. K. Okyay
Department of Electrical and Electronics Engineering, Bilkent University,
Ankara 06800, Turkey
e-mail: enesbattal@gmail.com

A. K. Okyay (✉)
UNAM—Institute of Materials Science and Nanotechnology,
Bilkent University,
Ankara 06800, Turkey
e-mail: aokyay@ee.bilkent.edu.tr

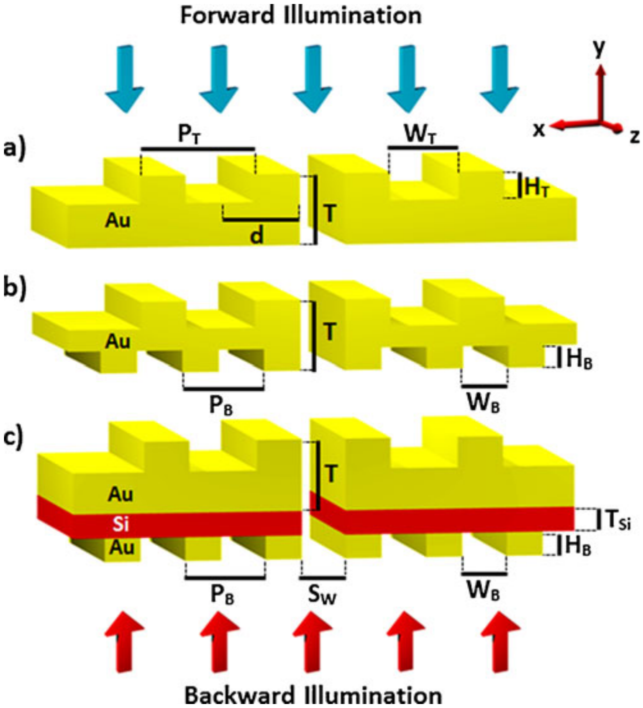


Fig. 1 Nanoslit with **a** single layer grooves, **b** double layer grooves, and **c** double layer grooves with silicon spacer

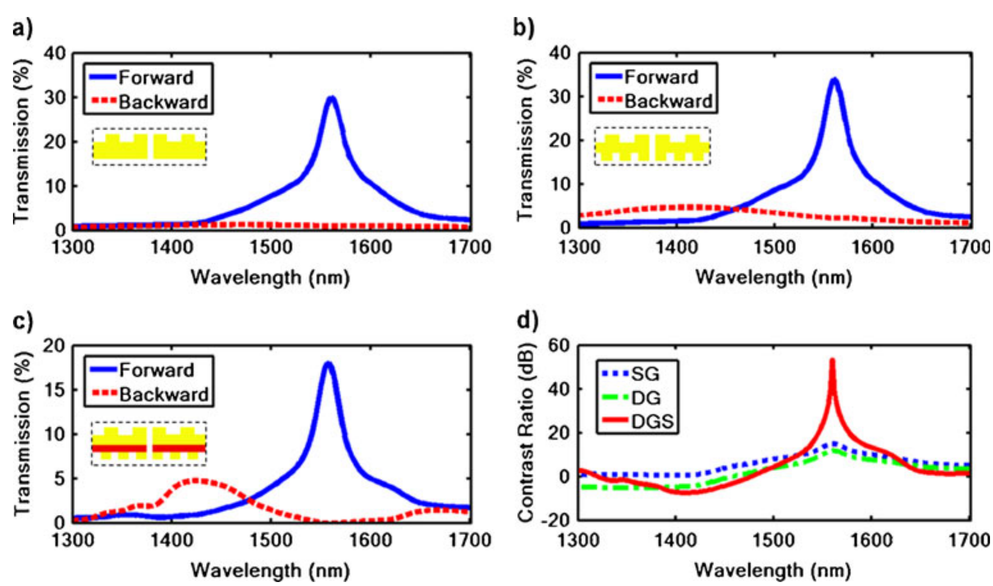
We comparatively investigate single grating (SG) structure with a flat metallic back surface (Fig. 1a), asymmetric double grating (DG) structure (Fig. 1b), and asymmetric double gratings with a dielectric (silicon) spacer (DGS; Fig. 1c). A single subwavelength nanoslit is located at the center of each device. Metallic grooves are assumed to be on a semi-infinite Au layer in all structures, to allow for surface plasmon polariton modes and enhanced transmission through the nanoslit in forward direction. The structure is assumed to be infinitely long in both *x*- and *z*-directions and finite in *y*-direction. We compute field profiles and transmission and reflection properties by two-dimensional finite-difference time-domain (FDTD) method using FDTD Solutions, Lumerical Inc. For the structures in Fig. 1, all boundaries are assumed to be perfectly matched layers. A normally incident transverse magnetic-polarized (electric field in the *x*-direction) plane wave is assumed to illuminate a 29-μm-wide spot centered on the slit. Metallic grooves are assumed to be in the illuminated area and a flat Au layer outside of the illuminating spot. Total-field scattered-field method is used to illuminate a finite width region with a plane wave [16]. The transmission values are calculated by normalizing the transmitted power (at a 3-μm distance) in one direction to the incident power. Contrast ratio is defined as the ratio between the forward and backward transmissions as defined in Fig. 1. The illumination is assumed to be uniform for the wavelength range of interest 1.3–1.7 μm, where there are no absorption losses in the silicon layer. The optical constants for Si and Au are obtained from Palik [17] and the size of the mesh covering the entire structure is taken constant at 10×10 nm.

We first investigate a single nanoslit at the center of a rectangular gold grating (Fig. 1a). In order to excite surface plasmon modes, the periodicity of the rectangular gratings is chosen according to the Eq. (1), the wave vector matching condition for normally incident waves,

$$m\frac{\lambda}{P} = \sqrt{\frac{\varepsilon_M \varepsilon_D}{\varepsilon_M + \varepsilon_D}}, \tag{1}$$

where λ is the wavelength of the incident wave, *P* is the periodicity of the grooves, *m* is an integer, and ε_M and ε_D are the dielectric constants of the metal (Au) and dielectric (air), respectively. The matching condition is satisfied for a wavelength of 1.56 μm when $m \approx 1$ and P_T=1,450 nm. The

Fig. 2 Forward and backward transmission spectra for **a** single grating (*SG*) structure, **b** double grating (*DG*) structure, and **c** double grating structure with a silicon spacer (*DGS*). **d** Contrast ratios for all structures



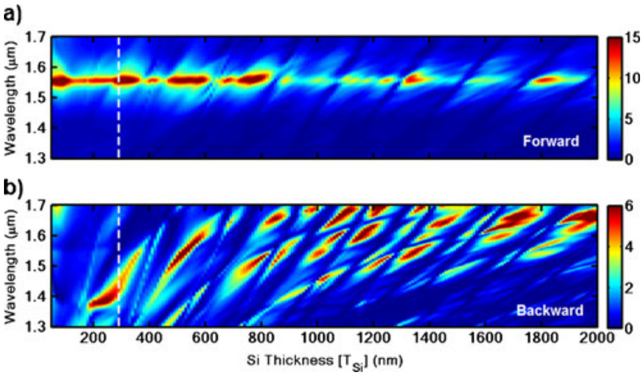


Fig. 3 Silicon thickness dependent spectra of **a** forward and **b** backward transmission of DGS structure

strength of the surface plasmon polariton (SPP) resonance is maximized when the width, W_T, and the height, H_T, of the corrugations are selected to be 890 and 250 nm, respectively. Maximum transmission through the slit can be obtained if the surface plasmons arising from the left and the right grooves constructively interfere at the exit face of the slit (symmetric condition), i.e., if their phase difference, θ is an integer multiple of 2π, $\theta=2k_{SP}(d+T)$ where k_{SP} is the in-plane wave vector of the surface plasmons, and $(d+T)$ is the propagation path length (as illustrated in Fig. 1). For $\lambda=1.56$ μm, this condition is achieved for $T=1{,}120$ nm and the slit width is chosen to be $S_W=210$. The geometrical parameters P_T, H_T, W_T, T, and S_W are kept fixed for all structures discussed henceforth. For SG structure, the forward and backward transmissions are plotted in Fig. 2a, exhibiting a peak forward transmission of 30 % with a contrast ratio of 30 (14.8 dB; Fig. 2d) at the wavelength of 1.56 μm while the backward transmission is approximately 1 % over the entire spectrum.

Ebbesen et al. [18] demonstrated that it is possible to enhance the forward transmission of a single subwavelength slit by introducing metallic corrugations at the exit side of the nanoslit at visible spectrum. For unidirectional

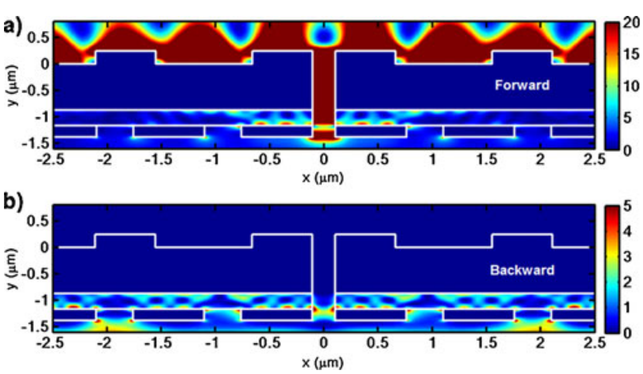


Fig. 4 E-field profiles of DGS structure for **a** forward and **b** backward illuminations

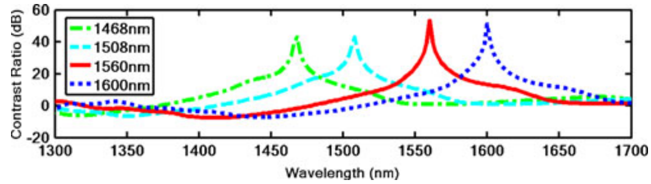


Fig. 5 Contrast ratio of DGS structures optimized for the wavelengths of 1,468 nm (*dotted dash*), 1,508 nm (*dashed line*), 1,560 nm (*solid line*), and 1,600 nm (*dotted line*)

characteristic, such corrugations should be carefully designed to avoid high backward transmission while increasing the forward transmission. Using a similar approach as Ebbesen et al. [18], we added grooves at the bottom side, to form a lamellar structure as shown in Fig. 1b. We designed the bottom metallic corrugations off resonance for backward illumination. Using bottom groove height, $H_B=220$ nm, width, $W_B=340$ nm, and period, $P_B=1{,}000$ nm, the coupling condition could be adjusted for weak excitation ($m\approx0.65$ in Eq. (1)) to obtain weakly excited surface plasmons at the bottom side. On the other hand, even though the excitation of surface plasmons on the bottom grooves is weak, the forward transmission increases due to the volumetric resonant coupling of the surface plasmon modes of the top and bottom grooves through the nanoslit, whereas the volumetric coupling in the case of backward transmission is weaker due to off resonance SPP excitation at the bottom side. Thus, the unidirectional characteristic of the structure is preserved. As shown in Fig. 2b, the peak forward transmission is enhanced from 30 to 34 % at $\lambda=1.56$ μm. However, the backward transmission is also increased up to 4.74 % despite the weak excitation of SPPs for back illumination. The peak contrast ratio is decreased from 29 to 14.9 (11.7 dB) at $\lambda=1.56$ μm as shown in Fig. 2d.

In order to realize much higher contrast ratios, strong suppression of the backward transmission is strictly necessary. Such contrast values can be achieved if the coupling of the incident light with the nanoslit is strongly blocked in the case of backward illumination. For this purpose, we introduced a silicon spacer in between the top and bottom gratings as

Table 1 Parameters of DGS structures corresponding to the optimized contrast ratios for the listed wavelengths

Peak wavelength (nm)	H_T (nm)	W_T (nm)	P_T (nm)	H_B (nm)	W_B (nm)	P_B (nm)	T (nm)	T_{Si} (nm)	S_W (nm)
$\lambda=1{,}468$	230	820	1,330	200	310	920	1,490	270	190
$\lambda=1{,}508$	240	840	1,370	210	320	950	1,560	280	200
$\lambda=1{,}560$	250	890	1,450	220	340	1,000	1,630	290	210
$\lambda=1{,}600$	260	910	1,480	230	350	1,030	1,680	300	220

depicted in Fig. 1c. The thickness of the top metallic structure is assumed the same as the overall thickness, T, of the previous structures (SG and DG) in order to maintain the constructive interference condition for the forward illumination.

We investigate the effect of the thickness of the spacer, T_{Si}, on the forward transmission (Fig. 3a). The spectral location of the forward transmission maximum is positioned around 1.56 μm and is insensitive to silicon thickness since the parameters of the top structure which induce the excitation of SPPs are independent of T_{Si}. However, the transmission maximum intensity is a strong function of silicon thickness and we observe modulation of the forward transmission maximum with silicon thickness. Au/Si/Au structure forms a metal–insulator–metal (MIM) waveguide which supports surface plasmons propagating at Au/Si interfaces [19]. The bandgaps observed in the figure roughly follow the relation of MIM waveguide modes, $T_{\mathrm{Si}=}m\lambda/(2n_{\mathrm{Si}})$, where m is an integer and n_{Si} is the refractive index of the silicon. Similarly, bandgaps in the backward transmission occur as a function of T_{Si} (Fig. 3b), but in this case, MIM waveguide modes and the plasmonic modes excited by the bottom grating resemble a coupled behavior such that the SPP modes split [19]. Ultrahigh contrast ratios can be achieved by crossing a local maximum of the forward transmission with a local minimum of the backward transmission. Hence, we assume a 290-nm-thick silicon layer in between the top and bottom rectangular gratings. With this configuration, backward transmission is heavily suppressed down to the order of 10^{-5}% as depicted in Fig. 2c. For the wavelength of 1.56 μm, an ultrahigh contrast ratio of 216,560 (53.4 dB) is achieved as plotted in Fig. 2d. At this wavelength, the electric field profiles of the structure for the backward and forward illuminations are demonstrated in subpanels a and b of Fig. 4, respectively. As the surface plasmons are excited on the metal/air interface for both forward and backward illuminations, they cannot be sustained at the silicon/air interface, thus, transmission can be obtained via volumetric coupling. In the case of forward illumination, SPPs exhibit an immense volumetric coupling through the nanoslit with the bottom gratings. However, there is still a loss in the peak forward transmission resulting in a transmitted power of 17.7 % (Fig. 2c). For the backward illumination, the transmission is heavily suppressed due to both weak excitation of surface plasmons at the bottom grooves and suppression of volumetric mode coupling as most of the light entering the slit is coupled into excited MIM waveguide modes in the dielectric spacer.

We also demonstrate in Fig. 5 that it is possible to tune the operation wavelength of the one-way optical transmission device by scaling the structural parameters while keeping ultrahigh contrast ratios. The corresponding structure parameters for the optimized operation wavelengths depicted in Fig. 5 are listed in Table 1.

In this work, we computationally investigated the transmitted power characteristics of single grooves at the top of flat metal layer, double-sided grooves, and the double-sided grooves with a silicon layer as a spacer. We demonstrated one-way transmission with an ultrahigh contrast ratio of 53.4 dB at the telecommunication wavelengths. We related the unidirectional behavior to different strengths of SPP excitations and volumetric coupling. We also demonstrated the tunability of peak wavelength of contrast ratio by arranging the parameters of the structure's geometry.

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