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Excitation of plasmonic waves in metal–dielectric structures by a laser beam using holography principles

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ABSTRACT

A method for development of gratings for effective excitation of surface plasmonic waves using holography principles has been proposed and theoretically analyzed. For the case of a plasmonic wave in a dielectric layer on metal, the proposed volume hologram is 1.7 times more effective than the simple grating of slits in the dielectric layer with the optimized period and slits' width. The advantage of the hologram over the optimized grating is in the refractive index distribution that accounts phase relationships between an exciting and an excited waves more correctly. The proposed holographic method is universal. As expected, this can be extended for effective excitation of different types of optical surface waves and modes of optical waveguides.

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1. Introduction

One of the actively developing fields of modern optics is optics of surface waves, including plasmonic waves [1]. Optical surface waves are applied for Raman spectroscopy [2,3], optical chemical and biosensors [4].

Among the most important devices for manipulation of surface waves (SWs) is a device for excitation of SWs. There are a lot of methods for excitation of SWs: SWs and, in particular, surface plasmons (SPPs) can be excited either by near field (e.g. from radiating molecules or quantum dots near the surface, along which the SW propagates [5] or from a probe of a near-field optical microscope [6]) or can be excited by far field (of a laser beam incident on the surface). In the last case, effective excitation of a SW requires the equality of components $\vec{k}_{\mathrm{SW}}$ and $\vec{k}_{\parallel}$ of the SW wave vector and the wave vector of the incident exciting wave along the surface (which is achieved in the Kretschmann configuration). Alternatively, structures breaking translational symmetry along the propagation direction of the SW should be fabricated. For instance, a periodic grating on the surface along which the SW propagates may break the translational symmetry.

The effect of an SPP excitation on a periodic grating on a metal surface by a plane wave is known from the beginning of the XXth century [7]. The effect manifests itself in a narrow dip in a reflectance spectrum of the grating (Wood effect). The position of the dip in a reflectance spectrum is described by the condition

$$\vec{k}_{\parallel} + m\vec{G} \approx \mathrm{Re}\vec{k}_{\mathrm{SPP}} \qquad (1)$$

of equality of a SPP wave vector $\vec{k}_{\mathrm{SPP}}$ and the projection $\vec{k}_{\parallel}$ of a wave vector of an exciting plane wave on the metal plane accurate within an integer number m of reciprocal lattice vectors $\vec{G}$ [8–10]. Thus, when the exciting wave is incident in the plane perpendicular to grating grooves the excitation condition (1) becomes $k_0 n \sin\alpha + (2\pi m/D) \approx \mathrm{Re}k_{\mathrm{SPP}}$. Here k_{SPP} is the magnitude of $\vec{k}_{\mathrm{SPP}}$ directed perpendicular to grating grooves, D is the grating period, k_0 - the wave number in vacuum, n - the refractive index of the medium where the exciting incident wave propagates, α - the angle of incidence of the exciting wave. In addition, the exciting wave must be p-polarized [10].

The efficiency of SWs excitation on periodic gratings may be, however, rather low (of about several percent of power) particularly in the case of small gratings with just several periods. To increase the efficiency of a SW/SPP excitation while keeping an exciting structure (e.g. grating) small (for the purpose of miniaturization) new approaches to develop such structures should be found. In the present paper, we show that using of holography principles can be such a new approach.

Let us note qualitative parallels between holography and excitation of SPPs by a grating on a metal surface. The grating itself is an analog of a hologram; an exciting wave incident on the grating from air is an analog of a reference or reconstructing wave; an excited SPP is an analog

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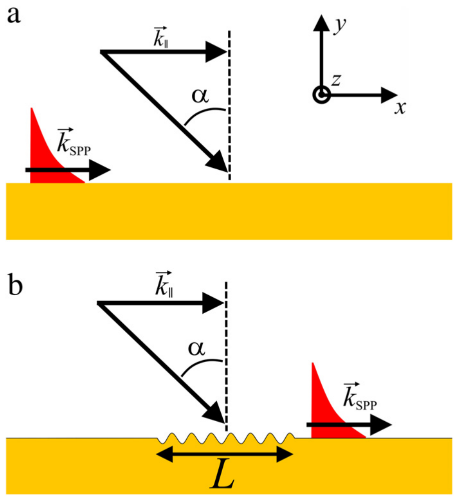

Fig. 1. Recording of a hologram (Fig. a) on a metal surface and reconstruction of the hologram (Fig. b) for an SPP excitation by far field. (a) For the recording of the hologram on the metal surface one must create an interference pattern of a reference wave incident from air at the angle α (the x-component of the wave vector of this wave is $\vec{k}_{\parallel}$) and the SPP (with the wave vector $\vec{k}_{\mathrm{SPP}}$). (b) The hologram in the form of modulated relief of the metal surface is illuminated by a reconstructing wave incident from air (exactly matching the reference wave used for the recording). As a result of the reconstructing wave scattering on the hologram, the SPP is excited. Air is shown by white color, metal—by gray color (orange online).

of an object wave, used when the hologram is being written, or an image obtained as a result of reconstruction of the hologram. The configuration for excitation of SPPs using principles of holography is shown in Fig. 1.

Let us consider, according to Fig. 1, excitation of an SPP by a plane wave on a hologram in the form of a metal surface relief modulation. The exciting wave is incident in the xy-plane. Suppose the metal surface relief in the hologram area is modulated such that the y-coordinate of the surface for each x is determined by the cross interference term of the exciting (reference) plane wave and the SPP, used for hologram recording. Since the electric field of the incident wave and the SPP on the metal surface depends on x as $\exp\left(ik_{\parallel}x\right)$ and $\exp\left(ik_{\mathrm{SPP}}x\right)$, respectively, the intensity of the sum of the incident wave and the SPP has the cross interference term depending on x as $\cos\left(\left(k_{\parallel}-k_{\mathrm{SPP}}\right)x+\varphi\right)$. Here φ is a phase shift between the exciting wave and the SPP independent on x. The hologram obtained in the form of the metal surface relief modulation $y(x) \propto \cos\left(\left(k_{\parallel}-k_{\mathrm{SPP}}\right)x+\varphi\right)$ is the grating with the period given by the condition (1) for the spectral position of a Wood anomaly. Thus, on this hologram an SPP is excited by the incident wave, coinciding (having the same x-component $k_{\parallel}$ of the wave vector) with the reference wave used for recording of the hologram [11]. In the approximation of small metal surface modulation, the incident wave after scattering on the hologram can be shown [12] to include the spatial spectral components $\exp\left(ik_{\parallel}x \pm i\left(k_{\parallel}-k_{\mathrm{SPP}}\right)x\right)$ and $\exp\left(ik_{\parallel}x\right)$, i.e. $\exp\left(ik_{\mathrm{SPP}}x\right)$, $\exp\left(i\left(2k_{\parallel}-k_{\mathrm{SPP}}\right)x\right)$ and $\exp\left(ik_{\parallel}x\right)$. The first of these three components corresponds to an excited SPP.

In the above arguments, we did not take into account possible finite aperture of the exciting wave and Ohmic losses in metal leading to decay of an SPP. However, in the case of metal with losses and finite aperture of the exciting wave the metal surface relief modulation remains nearly sinusoidal (in the area of the hologram recording) for small-area holograms with only several periods. Therefore, the efficiency of SPPs excitation on small-area holograms on the metal surface with weak modulation is nearly the same as for strictly periodic sinusoidal gratings with similar amplitude of metal relief modulation and size.

Holograms (in the form of metal surface relief modulation or in some other form) determined by interference of an exciting wave and an object wave are strictly periodic 1D gratings if phase fronts of each of the two waves are flat and the spatial intensity distribution of each wave is uniform in the area of hologram. Otherwise, holograms are more complicated. We expect that efficiency of plasmonic waves excitation on such holograms would in some cases be higher than on simple strictly periodic (e.g. analogous to those proposed in [13]) gratings with a period given by the Wood's condition (1). Indeed, although holography finds applications mainly for generation of images, this also can be used for efficient (in terms of transformed power) transformation of an exciting radiation into a required spatial mode (e.g. of a waveguide) [14].

In the recent years, a holographic approach for excitation of plasmonic beams of various complex configurations by laser beams incident on a metal surface from air [15–18] or by simple SPPs [19,20] has being actively developed. Holograms for excitation of plasmonic Airy [15,16,18], plasmonic Hermite–Gauss [15,18,21], plasmonic Bessel [18] beams on a flat metal surface and other plasmonic beams with rather complex field distributions [20] are developed and fabricated. One class of plasmonic holograms proposed in literature includes holograms in a form of metal surface modulation determined by interference of an exciting wave with a plasmonic beam being excited [11,15,18,22]. Holograms of another class are metasurfaces composed of optical nanoantennas whose characteristics and arrangement are customized to create a required amplitude–phase distribution of the scattered field [16,17,20,21]. However, application of holography for efficient (in terms of power) excitation of plasmonic SWs in metal–dielectric structures and modes of plasmonic waveguides is still to be analyzed.

This paper is devoted to theoretical study of efficiency of a plasmonic wave (PW) excitation in the structure metal/dielectric layer/air using holograms in the volume of the dielectric layer. The efficiency of excitation of the PW using holograms in the dielectric layer will be compared to that using periodic gratings of parallel slits in the dielectric layer.

2. Excitation of a plasmonic wave in a dielectric layer on metal using principles of holography

In this section, application of holography principles for excitation of a PW in a dielectric layer on metal is analyzed. Unlike holograms on a metal surface discussed in the previous section, holograms considered in this section are volume holograms in the dielectric layer. The structure analyzed here was composed of a layer (of infinite width) of photoresist poly(methyl methacrylate) (PMMA) of a thickness $h = 600\,\mathrm{nm}$ on the gold surface (see Fig. 2(a)). All the quantitative results presented in this paper are for the wavelength in vacuum $\lambda = 1.55$ μm. For this wavelength, the refractive index of PMMA was taken to be $n_{\mathrm{PMMA}} = 1.481$ [23] and the dielectric permittivity of gold—to be $\varepsilon_{\mathrm{Au}} = -115.1 + 11.3i$ [24]. The excited fundamental plasmonic mode (PW) of this PMMA layer on gold has the wave number $k_{\mathrm{PW}} = (1.433 + 0.003i)\,k_0$; this mode is the only TM-polarized guided mode of the structure. All the numeric results in the present paper were obtained with Comsol Multiphysics.

As an exciting wave, a beam $\vec{E}_{\mathrm{inc}}\exp\left(ik_{\parallel}x\right)$ incident in the xy-plane was taken (see the coordinate system in Fig. 2(a)). The beam had the Gaussian profile in the plane of incidence (having the focus on the gold surface) and $\vec{E}_{\mathrm{inc}}$ independent on z; $\vec{E}_{\mathrm{inc}}$ was polarized in the plane of incidence. The beam waist (in the xy-plane) was $w_0 = 6\lambda$, the angle of incidence $\alpha = -45°$ (i.e. x-projections of vectors $\vec{k}_{\parallel}$ and $\vec{k}_{\mathrm{PW}}$ had different signs). For a negative α, one of the two ("parasitic") side lobes of the field scattered from a hologram/grating is evanescent in the x-direction, because for this side lobe $|k_{\parallel} + \left(k_{\parallel} - k_{\mathrm{PW}}\right)| > \mathrm{Re}k_{\mathrm{PW}}$. Indeed, for a negative α $|2k_{\parallel} - k_{\mathrm{PW}}| \approx \mathrm{Re}k_{\mathrm{PW}} + 2|k_{\parallel}|$.

A hologram was recorded in the rectangular area of the PMMA layer (we name this area as Ω, see Fig. 2(b)) which covered the whole thickness of the layer in the y-direction, was infinite in the z-direction and had the length $L = 7\,\mu\mathrm{m}$ in the x-direction. The center of the hologram area Ω along the x-direction was at the focus of the incident beam.

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