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Excitation of channel plasmons in V-shaped grooves in the Kretschmann configuration

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ABSTRACT

Excitation of channel plasmons in a 1D array of V-shaped grooves in a metal film in the Kretschmann configuration was theoretically investigated. The channel plasmons were shown to be excited by the *s*-polarized incident wave. The excitation of channel plasmons in every single groove of the array manifested itself in a local minimum in the angular spectrum of reflection from the array of the grooves.

1. Introduction

The rapid development of plasmonic integrated optics is caused by predicted miniaturization of optical components compared to those made of dielectrics only [1]. In particular the fundamental mode of a plasmonic waveguide (WG) can be localized in a subwavelength area [2–6]. Also, low loss (down to 8% of power) passing of waves through sharp 90° bends of plasmonic WGs is theoretically predicted [7,8]. Plasmonic waveguides also may be used for transferring of small particles [9–11] and fabricating superluminescent diodes [12,13].

One of the promising types of plasmonic WGs is a V-shaped groove in a flat metal surface (see Fig. 1) [2,3]. The fundamental waveguide mode is localized in a narrow gap between two side walls of a groove (see Fig. 2) [14]. The strong localization between the side walls (along the *x*-axis) is due to weak penetration of the E-field into metal. Localization in the vertical direction (along the *y*-axis), in terms of the effective index method [3,15], is caused by the high effective index of a gap plasmon between two side walls; the narrower is the gap, the higher is the effective index. However, the effective index method is approximate and is not valid near the very bottom of the groove and near edges at the sides of the groove. Actually the electric field of the fundamental mode is mainly concentrated not at the very bottom but a little higher above the bottom (see Fig. 2). Also the amplitude of the field can have local maxima near edges at the sides of the groove [14].

Among the merits of V-shaped grooves as plasmonic WGs are:

1. -the possibility to make single-mode waveguides with subwavelength localization of the basic mode field [2],
2. -easy fabrication and compatibility with planar technology,
3. -low losses at sharp bends [7,16], relatively weak (in comparison with wedge plasmonic WGs) losses caused by scattering on structure imperfections, since the propagating wave is surrounded by nontransparent metal in three directions [7],
4. -good heat sink compared to WGs in the form of periodic chains of metal nanoparticles or WGs like metal nanowires surrounded with dielectrics.

Note that excitation of plasmonic waveguide modes in V-shaped grooves (the so-called channel plasmons) can be realized by end-fire coupling from a tapered end of an optical fiber [3,16], by groove-termination coupling mirrors [17], by fluorescent quantum dots inserted into a groove [18].

In the present paper, we studied the possibility of channel plasmon excitation in V-shaped grooves in the Kretschmann configuration [19]. This configuration is widely used for excitation of surface plasmon polaritons (SPPs) on a flat metal/dielectric boundary. In particular, surface wave-based plasmonic sensors are demonstrated in the Kretschmann configuration [20–22]. This

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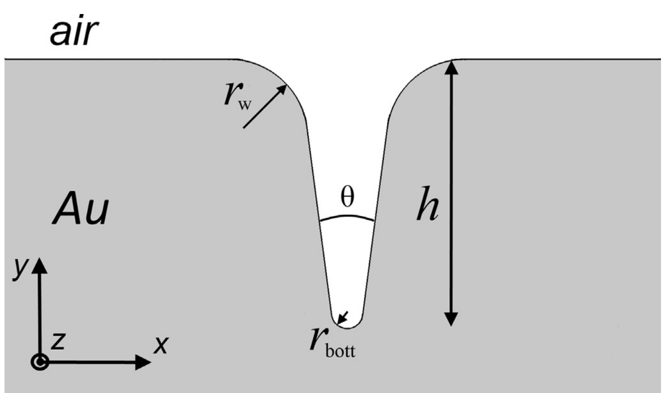

Fig. 1. Transverse section of a V-shaped groove. The gray area represents gold and the white area above gold corresponds to air.

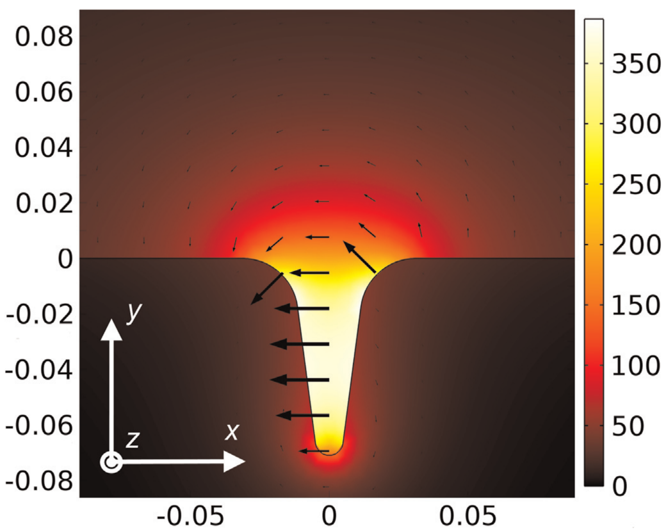

Fig. 2. Space distribution of the electric field amplitude of the waveguide mode of the groove. The E-field amplitude is indicated by color: the scale to the right is in arbitrary units. The scales below and to the left of the figure are space coordinates in microns. Black arrows indicate the components of the electric field in the cross-section plane of the groove (*xy*-plane).

configuration has been used only for excitation of SPPs and plasmons in dielectric loaded plasmonic WGs so far [23–27].

The structure of the present paper is the following. In Section 2, we describe particular geometric parameters of V-shaped grooves and characteristics of the corresponding channel plasmons in the grooves. To appropriately choose a polarization of the exciting wave in the Kretschmann configuration, we study field distribution and polarization direction of the channel plasmon fields in the grooves. In Section 3, we describe the Kretschmann configuration. For a selected wavelength, we consider excitation of plasmonic modes in a single groove and calculate a linear scattering cross section of the groove. Then we analyze excitation of plasmonic modes in a one-dimensional (1D) array of identical grooves as a function of the angle of incidence. From the experimental point of view, such an approach can be more useful for analyzing waveguiding properties of grooves than excitation of plasmonic modes in a single groove having subwavelength lateral dimensions. In Section 4, we present numerically calculated spectra of reflection from 1D arrays of grooves in the Kretschmann configuration both for *s*- and *p*-polarized incident exciting waves. We show that minima in the angular spectra of reflection (dependencies of a reflectance on an angle of incidence) are associated with excitation of channel plasmons in the grooves.

2. Channel plasmons in a V-shaped groove in metal

Modern techniques enable fabrication of plasmonic waveguides in the form of V-shaped grooves of various sizes [28–30]. In the paper [30] the possibility of fabrication of grooves with small angle between the side walls of ≈16° was shown. Before studying reflection spectra of V-shaped grooves in the Kretschmann configuration, we describe geometric parameters of the grooves and evaluate characteristics of the channel plasmons. We considered a V-shaped groove of a finite depth of $h = 70$ nm with a finite curvature radius of the metal surface at the bottom (see Fig. 1). The groove had an angle between the side walls of $\theta = 15°$, a curvature radius at the bottom of $r_{bott} = 5$ nm and a curvature radius at the side edges (wedges) of $r_w = 20$ nm. The groove was in a gold film with a dielectric permittivity of $\varepsilon_{Au} = -11.79 + 1.25i$ at a wavelength of $\lambda = 632.8$ nm [31]. For this wavelength the specified groove supported only one waveguide mode with an effective index of $n_{gr} = k_{gr}/k_0 = 1.117$. Here k_0 is the wave number in vacuum ($k_0 = \omega/c$) and k_{gr} is the wave number of the mode, calculated by use of COMSOL Multiphysics.

In Fig. 2, a distribution of the electric field amplitude of the waveguide mode at $\lambda = 632.8$ nm is shown. All the presented calculations were made for $\lambda = 632.8$ nm. We selected this wavelength because quantum dots (QDs) radiating in the wavelength range of 550–700 nm are available; the QDs can be used to compensate ohmic losses in plasmonic WGs [32]. It should be noted that qualitative results of our paper are valid for any wavelength at which SPPs at a metal/vacuum interface exist and when $|\varepsilon'| \gg \varepsilon''$ for the permittivity of metal.

One can see that the electric field of the waveguide mode is polarized mainly along the *x*-axis (Fig. 2). That is why the mode is excited efficiently by the incident *s*-polarized wave (E_s in Fig. 3, which corresponds to electric field polarization along the *x*-axis) in contrast to the case of excitation of a SPP, where the exciting wave should have the *p*-polarization (which corresponds to polarization perpendicular to the *x*-axis). Below we consider scattering of a plane wave on a single groove and on an array of grooves in the Kretschmann configuration.

3. Excitation of channel plasmons in a single V-shaped groove

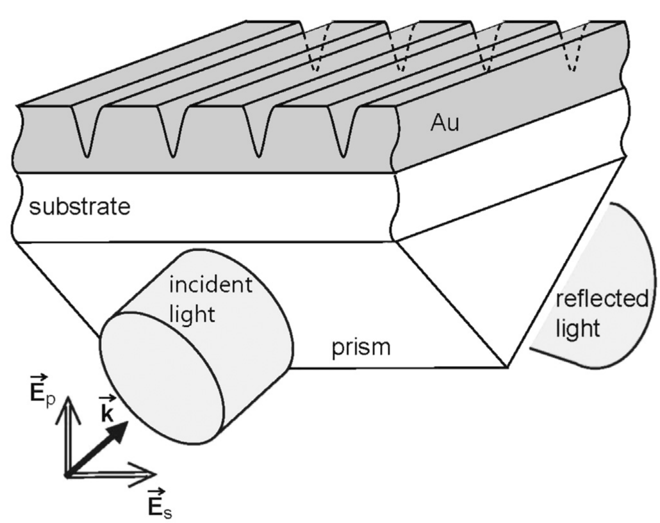

Fig. 3. The Kretschmann configuration for excitation of channel plasmons in an array of grooves in a gold film. Arrows indicate a direction of a wave vector $\vec{k}$ and polarization directions of electric fields of the exciting beam; *s*-polarization is along the *x*-axis in Figs. 1 and 2.