Available online at www.sciencedirect.com
ScienceDirect
Surface Science 600 (2006) 4771–4776
SURFACE SCIENCE
www.elsevier.com/locate/susc

Propagation of THz plasmon pulse on corrugated and flat metal surface

L.S. Mukina, M.M. Nazarov *, A.P. Shkurinov

Department of Physics and International Laser Center, M.V. Lomonosov Moscow State University, Moscow 119992, Russia

Received 6 June 2006; accepted for publication 28 July 2006
Available online 18 August 2006

Abstract

We report here experiments on surface plasmon excitation and propagation along corrugated and smooth aluminum surface in the terahertz frequency range. Narrowband plasmon excitation by a subpicosecond terahertz pulse is shown to be a transient process and plasmon propagation sufficiently changes its measured time profile. Plasmon propagation during its excitation and detection changes measured signal. We suggest to use parameters T (plasmon duration) and τ (plasmon lifetime) to describe the narrowband THz plasmon pulse. Plasmon duration and lifetime were defined and plasmon propagation lengths on smooth and corrugated surface were measured. Plasmon propagation length on flat surface turned out to be much smaller than it is predicted by the Drude model.

Keywords: Surface waves (plasmons); Diffraction; Metal surface; Diffraction grating

1. Introduction

At THz frequencies surface plasmon damping in metals considerably decreases and due to that the propagation length and lifetime increases in several orders of magnitude in comparison with optical frequencies. It allows one to use a metal surface as a simple waveguide for the waves on the THz frequencies. Because of the THz pulse duration is much less than plasmon lifetime and than plasmon traveling time through the area of its excitation, plasmon excitation is essentially a transient process. Later on we will call the THz surface plasmon pulse as TSP[1]. In the present paper coupling, propagation and outcoupling of TSP on corrugated and smooth aluminum surfaces is experimentally studied in the time-domain.

In the optical frequency range the excitation of surface plasmon on metal gratings is already studied in details [2] and moreover the plasmon excitation process by short pulse is analytically studied in [3]. The extension of plasmon temporal profile and the properties of the plasmon radiation are also discussed there. The influence of the finite size of the THz beam incoming on the grating surface (number of illuminated grating grooves) on plasmon excitation is studied in Refs. [4,5]. In THz spectral range broadband TSP excitation by edge and by prism was demonstrated recently [6,7]. THz plasmon excitation on periodical structures [8] was observed in several diffraction orders on a sequence of metallic cylinders. Guided THz waves on dielectric grating were studied in [9]. In [10] the excitation of THz plasmon on metal grating was observed and the amount of absorbed and radiated energy was evaluated. The THz pulse propagation on large (20 cm) distances on metal surface is studied in papers [11,1]. THz pulse propagated as Sommerfeld wave along the copper wire with small attenuation and dispersion, but localization was small there. In neighboring microwave frequency range surface plasmons on metal grating were also observed and described [12]. Attenuation, dispersion and localization of plasmon on metal–air interface is determined by the value of the dielectric function $\varepsilon(\omega)$ of the metal. From measurements in microwave and far IR regions [12,13] and the estimations based on the Drude model the $\varepsilon(\omega)$ value

* Corresponding author. Tel./fax: +7 495 9391106.
E-mail address: maxim@lasmed.phys.msu.su (M.M. Nazarov).

0039-6028/$ - see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.susc.2006.07.046

for aluminum is in the order of $\varepsilon = (-1 + i \cdot 20) \cdot 10^5$ for THz spectral range, that should correspond to TSP propagation length of several meters. In our previous work [14] we have demonstrated the possibility to excite narrowband surface plasmon on metal grating effectively by a THz pulse, dynamics TSP excitation and reradiation were studied there by the spectrochronography technique.

The goal of this work is to determine the TSP lifetime and to create a model, capable to describe the TSP properties after its propagation using the TSP temporal shape, duration, bandwidth and the amplitude. Parameters for the model are: THz beam size, incidence angle, diffraction order number, surface shape (corrugated or flat) and material dielectric function.

To analyze experimental results we made in the model the following assumptions: (1) To describe narrowband TSP two characteristic times must be used: plasmon duration T and plasmon lifetime τ. (2) TSP velocity v is constant and is equal to the speed of light, plasmon lifetime τ is unambiguously related to the propagation length l, plasmon duration T is related to the TSP length L. (3) The influence of T and τ on TSP characteristics is different.

2. Experiment

2.1. Experimental apparatus

We used the THz-time-domain spectrometer in the reflection geometry (Fig. 1) as it is described in Ref. [14]. The range of the incident angle variation was 30–60°. To generate a broadband THz pulse (via optical rectification) [15] ⟨1 1 0⟩ ZnTe crystal of 2 mm thickness was used. For the THz pulse detection via the electro-optic sampling technique we used the 4 mm thickness ⟨1 1 0⟩ ZnTe crystal. The output of the femtosecond laser (Tsunami-X1BB, Spectra Physics pumped by Millenia Pro) had pulse energy in order of 10 nJ, pulse duration of 70 fs and the wavelength centered on the 840 nm corresponding to maximal efficiency of THz generation and detection on 1 THz frequency. Signal to noise ratio in our experimental scheme was in the order of 10^3. A number of the experiments were carried out in the nitrogen atmosphere to get rid of atmospheric water vapor absorption lines.

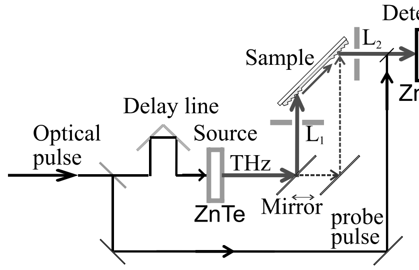

Fig. 1. THz spectrometer scheme in the reflection geometry. Dashed line – specular reflection configuration, solid line – plasmon propagation configuration.

A small portion of the laser beam was used for the detection of temporal profile of the THz field (Fig. 1). A collimated beam of THz radiation had a diameter of 25 mm and approximately Gaussian profile in the cross-section. If necessary the diaphragms (slits) L_1 and L_2 reduce the size of the incident and detected beams. The slit is centered on the THz beam axis and is oriented parallel to the grooves on the sample. The reference signal for the THz–TDS procedure was obtained with the substitution of the grating sample by the flat aluminum mirror (that later on is as the "Reference mirror"), perfectly reflecting THz beam in a wide frequency range. To couple and to outcouple the free space THz radiation we used corrugated metal surface – THz diffraction grating. To study the TSP propagation properties the THz beam was parallel shifted along the grating surface (see Fig. 1) to excite the TSP in various grating areas; angles of incidence and angels of the output radiation were preserved while moving THz beam along sample surface. By parallel shift of the flat *mirror_1* we also shifted the plasmon excitation area relative to the area of the plasmon detection (Fig. 1).

2.2. THz diffraction gratings

In the experiments we used two types of the THz diffraction gratings fabricated on the aluminum substrates with different groove profiles and periods. The ruled grating fabricated by milling of the given periodic profile on the monolithic aluminum substrate–later indicated as "$G1$", and the sample fabricated from the alumina foil of the 100 μm thick on the substrate with several equal gratings pressed on it–later indicated as "$G2$".

The sample "$G1$" is similar to one used in [14] has the period of $d = 0.3$ mm with the groove height $h = 75$ μm and the sawtooth profile. The grating length is $l_g = 8$ cm and the blaze angle is 15°.

The sample "$G2$" that is shown on the Fig. 2 consists of two diffraction gratings A and B connected by the flat surface region between them. The gratings of the $G2$ sample have the sine profile with the groove period of $d = 0.75$ mm and the groove height $h = 74$ μm. The G2 grating length is $l_g = 33$ mm. The size of the THz beam on the grating surface roughly corresponds to the grating size (at the incidence angle $\theta = 34°$). Additional third grating C was added on $G2$ for the second part of the experiments.

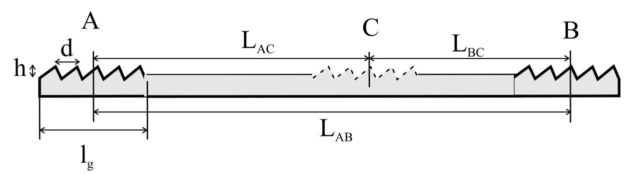

Fig. 2. Grating $G2$ scheme. At the first stage there were two gratings A and B, on the second stage third grating C was added. All three gratings have the same parameters: period d, groove height h and length l_g.