Thin-Film Frustrated Total Internal Reflection Filter with Plasmonic Nanoparticle Inclusions in the Layers

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Abstract. The influence of plasmonic nanoparticles embedded in the central and side layers of the frustrated total internal reflection filter on the resonant transmission of light is analyzed. It is shown that the frequency dispersion causes the splitting of the filter bandwidth and the angular splitting of the incident beam into several output beams.

1. Introduction

Resonant effects caused by wave interference occur when tunneling through a system of barriers. These effects are an optical analogy of quantum mechanical tunneling. They have found application in various areas of physics, including electron transfer in solid-state superlattices, integrated and fiber optics, and frustrated total internal reflection (FTIR) spectroscopy.

The FTIR filter was first proposed by Leurgens and Turner in 1947 [1]. It is known that FTIR filter uses resonant tunneling of light through a planar dielectric optical waveguide placed between two low refractive index thin films that act as potential barriers. Both integral and differential methods are used to solve Maxwell's equations to describe the FTIR effect in layered structures [2-5]. Currently, dielectric thin films with high thickness accuracy and low absorption and scattering losses are available. In [6] FTIR effect was considered in a circular polarization beam splitter [6]. High performance FTIR based thin-film linear polarizing beam splitter has been demonstrated in [7]. In [8], a FTIR based device was proposed for the spatial separation of an incident white light beam into three color beams. In [9] the effect of frequency dispersion in the resonator layer on the FTIR process has been investigated.

In this paper, the influence of the frequency dispersion caused by metal nanoparticles embedded in the layers of the FTIR filter on the resonant transmission of light is theoretically investigated. In comparison with the system considered in [9], here we analyze the effect of plasmonic nanoparticles embedded in the central and lateral layers. This allowed us to demonstrate the splitting of the incident beam into five spectrally and angularly separated output beams.

2. FTIR filter

The schematic view of the filter is shown in Fig. 1. The filter consists of a three-layer structure placed between two prisms with refractive indices $n_p$ and $n'_p$. A high-index central layer with a high refractive index and thickness $d_2$ is placed between two films with low refractive indices $n_i$ and $n'_i$. 

and thicknesses $d_1$ and $d_1'$, respectively. Angular and chromatic filtering of the incident light beam occurs due to the resonant diffraction effect when light propagates through a layered structure, i.e., the FTIR effect.

**Figure 1.** FTIR filter with nanoparticle inclusions in the layers.

The resonant condition for $s$-polarization is determined by the equation [8, 9]:

$$k'_1 d_2 = -\arctan \left[ \frac{k'_1 (q_z^2 + q'_z^2)}{q_z q'_z - k'_z^2} \right] - Q_3,$$

(1)

where

$$Q_3 = 2q_z k'_1 (q_z^2 - k'_z^2) \exp(-2q_z d_1) / [(q_z^2 + k'_z^2)(q_z^2 + k_z^2)], \quad q_z = (\omega / c) \sqrt{n_p^2 \sin^2 \varphi - n_i^2},$$

$$k'_z = (\omega / c) \sqrt{n_p^2 - n_p^2 \sin^2 \varphi}, \quad q'_z = (\omega / c) \sqrt{n_p'^2 \sin^2 \varphi - n_i'^2}, \quad k'_z = (\omega / c) \sqrt{n_i'^2 - n_p'^2 \sin^2 \varphi}$$

are the wavenumbers.

In the case of $p$-polarization, similar expressions for the resonance condition can be obtained.

For a fixed frequency of incident radiation, the dependence of the incidence angle on the dispersion is described by the expression:

$$\varphi(\omega) = \phi_0(\omega) + \frac{d_2^*}{d_{2\text{eff}}} \frac{\omega/c}{n_p^2 \sin 2\phi_0} \frac{\Delta \varepsilon'_z}{n_p^2 \sin 2\phi_0} + \left( \frac{1}{d_{2\text{eff}}} \right) \frac{2\Delta \varepsilon'_i}{n_p^2 \sin 2\phi_0},$$

(2)

where $\phi_0(\omega)$ is the incident angle in the absence of dispersion, $\Delta \varepsilon'_z$ and $\Delta \varepsilon'_i$ are the changes of the real part of the permittivity in the central and side layers, respectively, $d_2^* = d_2 + 2q_z \left( q_z^2 + k'_z^2 \right)$.

Let’s consider the layers with embedded metallic nanoparticles. Such a medium, in the framework of the Maxwell-Garnett model, is described by the effective dielectric permittivity. For spherical nanoparticles we have the relation [10, 11]:
\[
\varepsilon_{\text{eff}} = \varepsilon_m + \frac{3\eta (\varepsilon_p - \varepsilon_m)}{3\varepsilon_m + (1 - \eta)(\varepsilon_p - \varepsilon_m)},
\]

where \( \eta \) is the volume fraction of nanoparticles, \( \varepsilon_p \) is the dielectric permittivity of the nanoparticles, \( \varepsilon_m \) is the dielectric constant of the central layer.

In Fig. 2 the resonance incidence angle as function of the wavelength of s-polarized beam is shown for silver and gold nanoparticles. It follows that the resonant spectral lines shift when the angle of incidence of light changes. It is possible to get several resolved spectral lines at the output by changing the angle of incidence within certain limits. It can be seen that for a given angle of incidence, there are several resonant bands at once. This indicates that the resonant condition in the resonator is satisfied for several wavelengths at once. It follows from the simulation that the angular splitting of the beam occurs for a given wavelength, and for a certain wavelength of the incident beam, up to five output beams can be observed, separated by angles.

In Fig. 3 the spectral lines of transmitted light of FTIR filter with gold nanoparticle inclusions in the central and side layers are presented for the s-polarized incident beam. It follows that the spectral bandwidths decrease with the increase of the low-index layer thickness \( d_1 \) and the spectral line width \( \Delta \lambda = 27 \) nm was obtained at \( \lambda = 518 \) nm and \( d_1 = 500 \) nm. Five resonant bands exist at once for a given angle of incidence due to the fulfillment of the resonance condition for five wavelengths simultaneously.
Figure 3. Spectral lines of transmitted light: \( n_p = 2.0, n_1 = 1.38, n_2 = 2.0, d_1 = 500 \text{ nm}, d_2 = 70 \text{ nm}, \eta = 10^{-3}, \varphi = 50.18^\circ \).

It should be noted that resonant structures based on nanoparticle inclusions open up opportunities for creating infrared (IR) and terahertz technology devices that are inaccessible to conventional materials. In [11] acousto-optic filters with inclusions of metamaterials which provide ultra-narrow spectral lines due to resonant Bragg diffraction were considered. Large Goos-Hanchen (GH) shifts enhanced by the surface plasmon resonance in subwavelength gratings were demonstrated in [12]. In [13, 14] the resonance tunneling and GH and Imbert–Fedorov shifts of terahertz beams from graphene plasmonic metasurfaces were investigated.

3. Conclusions

Thus, the influence of photonic and plasmonic effects on the transmission spectrum of the FTIR filter with nanoparticle inclusions in the central and lateral layers is analyzed. The splitting of the filter bandwidth into several narrow-band spectral lines for a given incidence angle is shown. It is shown that an incident beam of a given wavelength splits into five angularly separated output beams. The considered thin-film beam splitter can be useful in many applications, such as color visualization systems, color display devices, sensors, spectroscopy, in spectral regions extending from the UV to the far IR range.

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