Numerical Design of an Optical Cavity with Plasmonic Diffraction Grating

D. S. V. Alves, and A. J. F. Orlando
ITA - Instituto Tecnológico de Aeronáutica
ITA, São José dos Campos-SP, 12.228-900, Brasil
savalves@ita.br, faro@ita.br

Abstract — This document presents the results of electromagnetic fields computation, based on finite difference in time domain, applied to metal-light interaction, tacking into account the surface plasmon modes around the interface metal-dielectric on the diffraction grating in an optical waveguide structure that is excited by a 1.3µm laser beam, generating a radiation lobe normal to the grating plane with 10.6µm.

I. Diffraction Grating

An optical waveguide structure is basically a thin film deposited on a transparent dielectric substrate. The three layers are the substrate layer, the guiding layer and the cladding layer with the respective refraction index n_s, n_g and n_c. The light cannot be guided unless $n_f > n_s > n_c$ and the thickness, T, of the guiding layer is above the critical thickness.

Fine periodic structures [1], fabricated in an optical waveguide structure are one of the most important elements for optical integrated circuit construction. They can be used as components for realizing wavelength dispersion, conversion, modulation and control of guided wavefront.

A grating structure for integrated optics, as shown in figure 1, can be described by the change in distribution of relative dielectric permittivity, Δε, caused by attaching the grating to a canonical waveguide structure.

Fig. 1. Waveguide structure with diffraction grating

When the grating is a periodic structure that extend along the waveguide plane (YZ plane), Δε can be writen by Fourier expansion as

$$\Delta\varepsilon(x,y,z) = \Sigma\,\delta\varepsilon_q(k).\exp(-jqk.r) \qquad (1)$$

$K=K_y\, e_y + K_z\, e_z$, $r = y\, e_y + z\, e_z$

within the grating layer, and Δε=0 outside. K is the grating vector that is normal to the grating plane and is correlated with the fundamental period Λ by $|K|=2\pi/\Lambda$. The coefficient Δεq(x) denotes the amplitude of the q-th Fourier component, and satisfies $\Delta\varepsilon q = \Delta\varepsilon q^*$ because Δε is real.

When an optical wave that is characterized by a propagation vector β is incident in the grating region, wave components with propagation vectors β + qK, called space harmonics, are produced as the result of the phase modulation Δε. These space harmonics can propagate as a mode, as long as propagation vector value allows for propagation in the structure. This means that a relation

$$\beta_b = \beta_a + qK,\ q = 0, \pm1, \pm2, \dots \qquad (2)$$

is required for the coupling between two waves, a and b, characterized by the propagation vectors β_a, β_b to take place. Here, q is the order of the coupling. Equation (2) gives the coupling condition whwre the waves and Δε have an infinite expanse in space. In many optical integrated circuits, Δε is nonzero only in the vicinity of the waveguide YZ plane and extend a small way in the X direction. These relations can be depicted as a wave vector diagram with vectors β_a, β_b and K. Such a diagram is used to determine the combinations of waves involved in the coupling.

The coupling between guided mode and radiation mode occurs when the grating period satisfies the condition $w/c=K=2\pi/\Lambda$. Such gratings are called grating couplers because they are used as input-output couplers for excitation and decoupling of guided waves [2]. A guide wave propagating along the Z direction in the structure with propagation β_0 is associated with the space harmonics characterized by propagation constants

$$\beta_q = \beta_0 + qK\ (q = 0, \pm1, \pm2, \dots) \qquad (3)$$

where β_0 is close to the propagation constant of a guided mode in a wave guide without grating.

If $|\beta_0| < n_cK$ or $|\beta_q| < n_sK$, the qth harmonics radiate into the cladding and/or the substrate at angles determined by

$$n_c k \sin\theta_q^c = n_s k \sin\theta_q^s = \beta_q = Nk + qK \qquad (4)$$

II. Plasmonics

Surface plasmons are electromagnetic modes that arise from the interactions between light and mobile surface charges, typically the conduction electrons in metals [3]. This light-metal interaction leads to surface modes having greater momentum than light of the same frequency. The electromagnetic fields associated with them cannot propagate away from the surface. These modes on a planar metal surface are thus bound to that surface and guided by it, propagating until their energy is dissipated as heat in the metal. Some properties of surface plasmons are important: the propagation length, δ_s, the wave length, λ_s, the penetration depth into dielectric, δ_d and into metal, δ_m.

The dispersion relationship between the frequency and in-plane wave-vector for SPPs propagating along the interface between a metal and a dielectric can be found by looking for surface mode solutions of Maxwell's equations under appropriate boundary conditions. Considering the dielectric constant ε_d and dispersive metal permittivity $\varepsilon_m(\omega)$, with its real and imaginary parts, surface plasmon dispersion relation K_S, wavelength λ_S and propagation length δ_S can be obtained by the equations:

$$K_s = K_0 \sqrt{\frac{\varepsilon_d . \varepsilon_m(\omega)}{\varepsilon_d + \varepsilon_m(\omega)}} \tag{5}$$

$$\lambda_s = \lambda_0 \sqrt{\frac{\varepsilon_d + \varepsilon_m^{'}}{\varepsilon_d \varepsilon_m^{'}}} \tag{6}$$

$$\delta_s = \lambda_0 \frac{(\varepsilon_m^{'})^2}{2\pi \varepsilon_m^{''}} \left(\frac{\varepsilon_m^{'} + \varepsilon_d}{\varepsilon_m^{'} . \varepsilon_d}\right)^{3/2} \tag{7}$$

III. Numerical Results

We report a numerical analysis based on FDTD [4] applied to a fine designed grating coupler considering its period, high and filling factor yielding an efficient coupling of guided mode and radiation mode. The diffraction grating is designed to radiate isotropically and enhance the radiation mode in the near field. that stimulates the response from a layered biologic medium. Figure 2 shows the the propagation of guided and radiation modes.

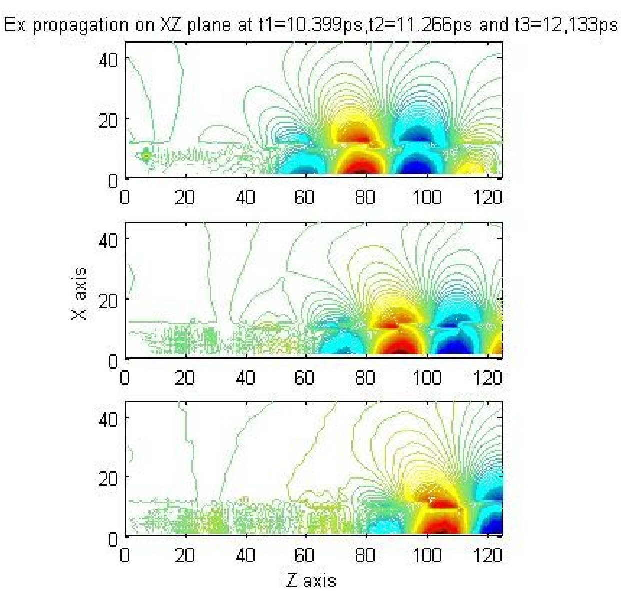

Fig. 2. Coupling of guided mode and radiation mode

Since surface plasmons are bounded to the metal surface and cannot propagate away from the surface, these surface guided modes are efficiently conversed to radiation mode.

Tacking into account that metal behaves like mirror, the plasmonic diffraction grating must be placed on the film-substrate interface, as shown in figure 3.

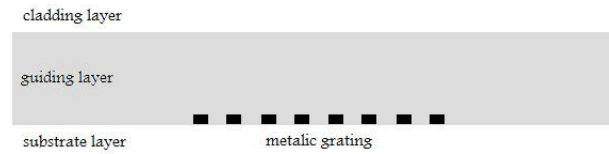

Fig. 3. Plasmonic diffraction grating

Considering that radiation modes leave the waveguide toward the cladding and substrate layers, a symmetrical cavity were improved to obtain a radiation lobe normal to the optical waveguide structure, as shown in figure 4.

Fig. 4. Optical cavity with plasmonic diffraction grating

The finite-difference time-domain method solves a wide range of scientific problems involving the analysis of electromagnetic wave phenomena and the design of electromagnetic wave devices and systems. Current FDTD modeling applications range from ultra low frequencies (geophysical phenomena) through microwave (radar) to visible lights (biophotonics). This work verified the application of FDTD for a optical device, considering the coupling of surface plasmons and radiation modes in a plasmonic diffraction grating cavity excited by a 1.3μm laser. The metalic grating was fine design to obtain an output radiation of 10.6μm.

IV. References

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