LIGHT TRAPPING BY MEANS OF ELECTRIC FIELD ENHANCEMENT IN METALLIC GRATINGS

F.J. Llopis[1*], M. M. Jakas[1] and I. Tobías[2]
[1]Departamento de Física Fundamental y Experimental, Electrónica y Sistemas.
Universidad de La Laguna, c/Astrofísico Sánchez s/n, E-38025 La Laguna, S.C. de Tenerife, Spain.
Corresponding autor: fllopis@ull.es
[2]Instituto de Energía Solar.
ETSI Telecomunicación, Universidad Politécnica de Madrid, E-28040 Madrid, Spain.

ABSTRACT: The enhancement of the electromagnetic field within the grooves of a metallic diffraction grating is analyzed. A perfect conductor, rectangular-shaped diffraction grating is assumed, therefore, the field enhancement analyzed in this work is due to resonances caused by the structure itself, and not to the so-called surface-plasmon resonances which are observed to be influenced by metal properties as well. The modal approach has been employed for calculations. Basically, the squared amplitude of the electric field within the grooves is calculated as a function of the wavelength of the incident light. Similarly, the behaviour of the structure when exposed to a conical bundle of light is also analyzed. The present results show that a field intensity enhancement of the order of 100 is achievable. However, the spectral width of the resonances decrease with increasing enhancement as is expected.

Keywords: Light Trapping; Optical Properties; Absorption

1 INTRODUCTION

Since the performance of silicon solar cells is affected by partial absorption of infrared wavelengths, textured surfaces have been commonly employed to confine light by means of total internal reflection [1] . This approach, however, is not always easily applied in thin film devices. On the other hand, recently proposed devices based on up-conversion schemes, or intermediate band solar cells (IBSCs), also exhibit low absorbance in the infrared range. In both cases, it has been suggested that the conversion efficiency relies on the achievement of high electromagnetic densities [2,3].

Light absorption increases with the squared amplitude of the electric field, which in turn can be boosted by means of resonant enhancement. To this end, in this work we focus our attention on the behaviour of the electromagnetic field inside the grooves of rectangular-shaped metallic gratings. It has been shown previously that, at certain wavelengths, the intensity of the electric field can be enhanced up to two orders of magnitude inside the grooves if geometrical features are properly chosen The electric field intensity is reinforced by means of constructive interference, in a similar manner as the resonances supported by electromagnetic resonators [4, 5].

The results of this work show that the enhancement increases with the groove depth to width ratio and that the spectral width of the resonances behaves in the opposite sense. The enhancement of the electric field is assumed to be linked to the resonances produced by the ideal structure itself. The so called surface plasmon resonances (the excitation of collective oscillations of the electronic surface density), are influenced by the metal properties [5], and are not considered in this work.

2 OUTLINE OF THE THEORY

As depicted in figure 1, we assume that a perfectly conducting grating with groove spacing d is exposed to a monochromatic TE polarized wave with a vacuum wavelength λ. The refractive index of the incidence medium is ν_1. The groove depth and aperture are h and c, respectively. The incident electric field can be expressed as

$$E_{zi}(x,y) = \exp[i(\alpha_0 x - \chi_0 y)] \quad , \tag{1}$$

where the components of the incident wavevector are given by $\alpha_0=\kappa\nu_1 sin\theta$ and $\chi_0=\kappa\nu_1 cos\theta$, with θ being the incidence angle and $\kappa=2\pi/\lambda$ the vacuum wavenumber.

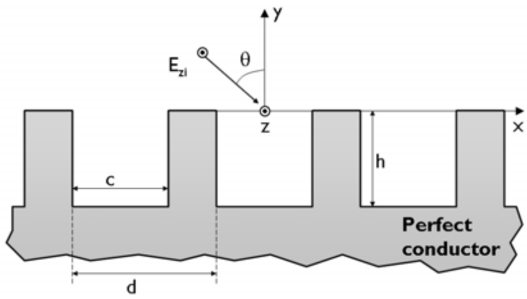

Figure 1: Grating illuminated by TE polarized light.

The interaction between the incoming wave and the grating results in [4]:
(1) A reflected electric field that can be expressed in terms of the plane wave expansion

$$E_R(x,y) = E_{zi}(x,y) + \sum_{n=-\infty}^{\infty} A_n \exp[i(\alpha_n x + \chi_n y)] \quad , \tag{2}$$

where A_n is the amplitude of the nth reflected plane wave, whose wavevector componentes are $\alpha_n= \alpha_0+2\pi n/d$ and $\chi_n=[(\kappa\nu_1)^2- \alpha_n^2]^{1/2}$.

(2) An electric field inside the grooves that can be expressed by the modal expansion

$$E_M(x,y) = \sum_{m=1}^{\infty} a_m \phi_m(x,y) \quad , \tag{3}$$

where:
$\phi_m(x,y)=\sin[\mu_m(y+h)]\sin(m\pi x/c)$ if m is even,
$\phi_m(x,y)=\sin[\mu_m(y+h)]\cos(m\pi x/c)$ if m is odd,
and $\mu_m = [(\kappa\nu_1)^2 -(m\pi/c)^2]^{1/2}$.

We have employed the procedure reported in [4] to calculate the modal amplitudes. The main results are discussed in the following section.

3 RESULTS

3.1 TE polarization

For normal incidence, the behaviour of the internal TE electric fields can be more easily discussed if the conditions for operation of the monomode regime hold [4]. In this case, the only non-imaginary *y*-spatial frequency is that of the *m*=1 mode (fundamental mode). The remaining modes, i.e. *m*=2,3,…, are evanescent. The resonance wavelengths are close to the zeros of $\tan[\mu_1(\lambda)h]$, with μ_1 being the *y*-spatial frequency of the fundamental mode. These quasi-resonance wavelengths are expressed as

$$\lambda_j = 2\nu_1(j^2/h^2+1/c^2)^{-1/2},\ j=1,2,\ldots$$

As appointed in [4], the magnitude of the electric field will be larger the smaller is $\mu_1(\lambda_j)$. This implies to select *h* as large as possible. In the limit $h \to \infty$ we find $\lambda_j = 2\nu_1 c$. Thus, we have an estimate of the groove width *c* for a given resonance wavelength, provided that grooves are deep enough.

The electric field enhancement can be estimated in terms of the squared amplitude of the electric field at the centre of the grooves. The plots depicted in figure 2 have been obtained for ν_1=3.6, a resonant wavelength λ=4.13 μm (1.24/0.3 eV) and a ratio *d*/*c*=1.3. The enhancement increases with the *h*/*c* ratio and can be of the of the order of 100 (or even greater). The main peaks are also located near our objective for the greater *h*/*c* ratios, as expected. But the spectral width decreases with the *h*/*c* ratio. (For a more comprehensive discussion of the spectral behaviour of the electric field, see Ref. [6]).

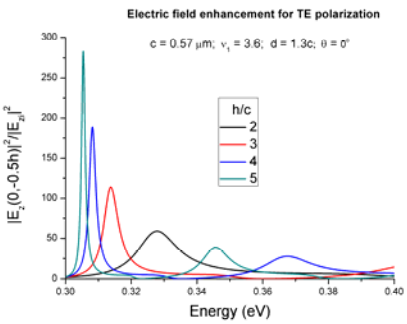

Figure 2: Plots of the squared magnitude of the normalized electric field for *d*=1.3c and different depth to width ratios.

It must be pointed out that prototype IBSCs operating with concentrated light can be exposed to a conical bundle of light of about 11º for concentration levels of 1000× [3]. Thus, bearing in mind that the case of oblique incidence must not be disregarded, we have performed the calculation of the electric field enhancement for several incidence angles (figure 3). The same *d*/*c* ratio has been assumed. It can be noticed that the enhancement levels for θ=0º and θ=10º are nearly the same. The main peaks for θ=30º drop to about the half of normal incidence ones, and the enhancement effect is fairly small for angles above 50º.

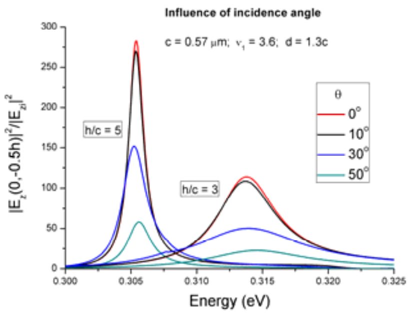

Figure 3: Influence of the incidence angle.

3.2 TM polarization

When employing the aforementioned criterion for TM polarization, we cannot expect a noticeable enhancement of the electric field. This drawback cannot be overcome since the fundamental mode for TM polarization is enhanced for wavelengths that obey a quite different condition, i.e. $\cos(\mu_0 h)$=0 [5]. The electric field can be enhanced up to a factor of $2d^2/c^2$, which implies a decrease of the grooves size. The simultaneous enhancement of the TE and TM electric fields can be attained by imposing a condition of surface resonance ($d=\lambda/\nu_1$) [5]. However, the results obtained so far show that the enhancement is very sensitive to changes of the width *c* and depth *h* of the grooves [6].

4 SUMMARY

We have investigated the possibility of increasing the absorption of solar cells by using a metallic grating. Results in this work show that a noticeable enhancement of the electric field can be achieved for TE polarization if grooves are deep enough for small incidence angles. Since the internal field enhancement obey quite different conditions for TE and TM modes, a condition that ensure the existence of surface resonances can be employed instead [5,6].

5 ACKNOWLEDGEMENTS

This work has been supported by the European Union (EU) Program IBPOWER (211640).

6 REFERENCES

[1] B. Sopori, in “Handbook of Photovoltaic Science and Technology”, A. Luque and S. Hegedus (eds.), Wiley (2004) 307.
[2] H. Shpaisman, O. Niitsoo, I. Lubomirsky, and D. Cahen, Sol. Energy Mater. Sol. Cells 92 (2008) 1541.
[3] A. Luque, A. Martí, Advanced Materials 21 (2010) 1.
[4] A. Wirgin, A. A. Maradudin, Phys. Rev. B 31 (1985) 5573.
[5] F. J. García-Vidal, J. Sánchez-Dehesa, A. Dechelette, E. Bustarret, T. López-Ríos, T. Fournier, and B. Pannetier, J. Lightwave Tech. 17 (1999) 2191.
[6] F. Llopis, I. Tobías, and M. M. Jakas, paper accepted for publication in J. Opt. Soc. Am. B.