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# Optimization of light polarization sensitivity in QWIP detectors

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ABSTRACT

The current development of QWIPs (Quantum Well Infrared Photodetectors) at III–V Lab led to the production of 20 μm pitch, mid-format and full TV-format LWIR starring arrays with excellent performances, uniformity and stability. At the present time III–V Lab, together with TOL (Thales Optronics Ltd.) and SOFRADIR (Société Française de Détecteurs Infrarouges), work on the demonstration of a 20 μm pitch, 640 × 512 LWIR focal plane array (FPA) which detects the incident IR light polarization. Manufactured objects present a strong linear polarization signature in thermal emission. It is of high interest to achieve a detector able to measure precisely the degree of linear polarization, in order to distinguish artificial and natural objects in the observed scene.

In this paper, we present a theoretical investigation of the optical coupling in polarization sensitive pixels. The QWIP modeling is performed by the Finite Difference Time Domain (FDTD) method. The aim is to optimize the sensitivity to light polarization as well as the performance of the detector.



## 1. Introduction

In regular QWIP FPAs one uses 2D diffraction patterns (e.g. 2D gratings) that allow coupling of incident light with any polarization (see Fig. 1). By replacing the 2D pattern with a 1D pattern (e.g. lamellar grating) a polarization sensitive pixel is achieved. In theory, for infinite pixels only the polarization parallel to the 1D modulation direction (TM incident wave) is absorbed.

For a finite size pixel, edge coupling of the incident light also occurs: a pixel with no diffraction grating or a pixel with a lamellar grating illuminated by a TE incident wave will have a non-zero responsivity. The total responsivity is therefore a combination of the edge contribution and the diffraction pattern contribution.

The diffraction pattern coupling efficiency decreases with decreasing pixel size (reduction of the number of diffracting periods), so that the total responsivity decreases too (yet, the responsivity is non-zero even for very small (<10 μm) pixels. This effect is likely to affect the sensitivity to the incident polarization, so the evolution with the pixel size has to be investigated.

In this paper, we present a theoretical investigation of the optical coupling in polarization sensitive pixels. The QWIP modeling is performed by the Finite Difference Time Domain (FDTD) method in three dimensions. We first describe the material properties used in our modeling. Then we describe the geometrical properties of a polarimetric elementary detection cell and the principle of a polarimetric focal plane array (FPA). We depict the information about the incident light polarization which can be obtained with such a structure. Afterwards, an exhaustive theoretical study of the optical coupling parameters is achieved. First, we study the influence of the pixel size on the efficiency of the incident polarization discrimination. In a second time, we study the optical coupling in a small pixel (<20 μm): the influence of the grating parameters (grating height, filing factor) as well as the quantum dielectric structure are investigated.

## 2. Material properties

The first parameters to focus on are the intrinsic properties of the different layer materials composing the pixel structure. It is well known that quantum well structures present an anisotropic dielectric permittivity, while the other layers such as the electric contacts present an isotropic dielectric permittivity. Numerical modeling must precisely take into account these fundamental properties. The dielectric permittivities computations are based on the Drude model in the electric contacts and are given by:

$$\varepsilon_{\text{contact}}(\omega) = \varepsilon_\infty - \frac{\omega_p^2}{\omega^2 - i\Gamma\omega}, \quad \omega_p^2 = \frac{Ne^2}{m^*\varepsilon_0},$$

$\omega_p$ is the plasma frequency, $N$ is the doping density, $m^*$ is the effective mass of the electrons inside the material, $\varepsilon_\infty$ is the dielectric permittivity of GaAs at high frequencies, the diffusing time of the electrons is calculated experimentally from laboratory measurements [1].

The dielectric permittivity inside the active region is modeled by a tensor as follows:

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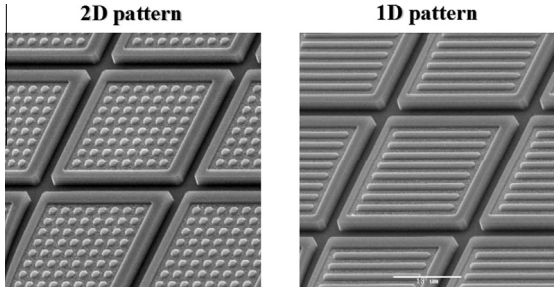


**Fig. 1.** Two different diffraction patterns (25 μm pitch).

$$\varepsilon_{ZA}(\omega) = \begin{pmatrix} \varepsilon_{xx} & 0 & 0 \\ 0 & \varepsilon_{yy} & 0 \\ 0 & 0 & \varepsilon_{zz} \end{pmatrix},$$

where $\varepsilon_{xx} = \varepsilon_{yy}$, $x$ and $y$ are the directions parallel to the quantum wells layers and $z$ is the perpendicular direction. The different layers composing the active region are very thin compared to the wavelength inside the material, so we choose to define a mean dielectric permittivity in the entire region. We first calculate the dielectric permittivity in the potential barriers, which is assumed to be isotropic, as follows:

$$\varepsilon_{\text{barrier}} = \varepsilon_{\text{GaAs}} \cdot (1 - \%_{\text{Al}}) + \varepsilon_{\text{AlAs}} \cdot \%_{\text{Al}},$$

where $\varepsilon_{\text{GaAs}}$ and $\varepsilon_{\text{AlAs}}$ are the dielectric permittivities of the corresponding materials and $\%_{\text{Al}}$ is the fraction of aluminum composing the potential barriers. Then the dielectric permittivity in the quantum wells along the $x$ and $y$ axis is calculated from a Drude model in the same manner as the electric contacts. The dielectric permittivity along the $z$ axis is calculated from a Lorentz model:

$$\varepsilon_{zz} = \varepsilon_{\text{GaAs}} + f\frac{\omega_p^2}{\omega_{12}^2 - \omega^2 - i\omega\gamma},$$

where $f$ is the oscillator strength of the inter-subband transition, $\omega_{12}$ is the transition frequency (peak of absorption) and $\gamma$ is the relaxing time of the inter-subband transition. The mean dielectric permittivity is then defined as follows:

$$\varepsilon_{xx,yy,zz} = \frac{\varepsilon^{\text{well}}_{xx,yy,zz} \cdot L_{\text{well}} + \varepsilon^{\text{barrier}}_{xx,yy,zz} \cdot L_{\text{barrier}}}{L_{\text{well}} + L_{\text{barrier}}},$$

where $L_{\text{well}}$ and $L_{\text{barrier}}$ are the width of the wells and the barriers respectively.

Typical examples of the evolution of the different permittivities in function of the wavelength are presented in Fig. 2. These were calculated for a classical QWIP produced at the III–V Lab which absorption peak is equal to 8.5 μm. The dielectric permittivity of undoped materials is determined from experimental data [2]. The last type of material composing a QWIP structure is the metal of the diffraction grating which is deposited at the top of the pixel. Due to numerical resources limitation, it is modeled by a perfect electric conductor. As in the Long Wave Infrared (LWIR) the incident light frequencies are far from the plasma frequency of the metal, this assumption is quite valuable (a small part of the incident light is absorbed inside the metal).

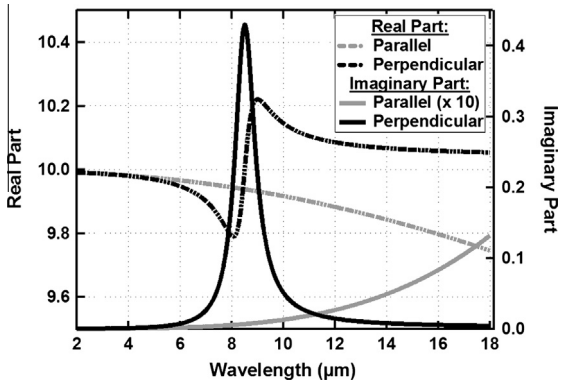


**Fig. 2.** Evolution of the dielectric permittivity in function of the wavelength inside the active region of a QWIP detecting in the LWIR (the absorption peak is equal to 8.5 μm).

We are now going to present the principle of a polarimetric FPA. With a two by two pixels elementary cell, with different gratings orientations, the Stokes parameters of the incident light can be determined. More particularly, the degree of linear polarization of the objects composing the observed scene can be calculated.

## 3. Principle of a polarimetric focal plane array

The IR light emitted by objects with a non-zero temperature may present a polarization signature. Different information can be obtained by analyzing it, such as surface roughness and artificial nature [3,4]. Polarimetric imagery can therefore be very useful to detect manufactured objects in a "natural" scene (buildings, vehicles, objects lying on the floor, etc.). Ideally, in order to collect all the information about the polarization of the detected flux, every component of the Stokes vector has to be calculated. The Stokes vector can be defined as follows:

$$S = \begin{pmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{pmatrix} = \begin{pmatrix} \langle E_x E_x^* \rangle + \langle E_y E_y^* \rangle \\ \langle E_x E_x^* \rangle - \langle E_y E_y^* \rangle \\ 2Re(\langle E_x E_y^* \rangle) \\ -2Im(\langle E_x E_y^* \rangle) \end{pmatrix} \propto \begin{pmatrix} I_0 + I_{90} \\ I_0 - I_{90} \\ I_{45} - I_{135} \\ I_G - I_D \end{pmatrix},$$

where $E_x$ and $E_y$ are the electric field components of the incident light, parallel and perpendicular to the lamellar grating respectively. As manufactured objects often exhibit a strong linear polarization signature, we mainly focus on the degree of linear polarization which is defined as:

$$D_{LP} = \frac{\sqrt{S_1^2 + S_2^2}}{S_0}.$$

So, a minimum of 3 pixels is needed to get the three first components of the Stoke vector. For evident symmetry reasons imposed by the FPA format an elementary cell of two by two pixels has to be conceived. Fig. 3 presents an image obtained with a scanning electron microscope (SEM) of a polarimetric FPA realized at the III–V Lab. The elementary cell is highlighted by a white dashed line. The 4 pixels present four different gratings orientations which allow us to calculate the three first components of the Stokes vector (i.e. horizontal, vertical, oblique ± 45°). An integrated system of micro-scanning rebuilds the final image from four successive frames, each frame containing the requested polarimetric information. In practice, one measures the current delivered by each pixel as a pertinent data. Another pertinent data is the integrated spectral response of the pixels.

We present in Fig. 4 the spectral response measured on pixels which gratings are oriented perpendicularly toward each other. The sample was mounted in a laboratory cryostat with an $f$-number equal to 1.6 and cooled down to 60 K (background limited regime). The photo-current was measured with a Fourier Transform InfraRed (FTIR) interferometer. The incident light is collimated, linearly polarized and perpendicular to the grooves of one of the 2 pixels (so parallel to the groove of the other). Comparison with the spectral response of a pixel without grating is also shown. We will use the notations presented in Fig. 5 for the integrated