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Optical-based spectral modeling of infrared focal plane arrays

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ABSTRACT

We adopt an optical approach in order to model and predict the spectral signature of an infrared focal plane array. The modeling is based on a multilayer description of the structure and considers a one-dimensional propagation. It provides a better understanding of the physical phenomena occurring within the pixels, which is useful to perform radiometric measurements, as well as to reliably predict the spectral sensitivity of the detector. An exhaustive model is presented, covering the total spectral range of the pixel response. A heuristic model is also described, depicting a complementary approach that separates the different optical phenomena inside the pixel structure. Promising results are presented, validating the models through comparison with experimental results. Finally, advantages and limitations of this approach are discussed.

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1. Introduction

Infrared Focal Plane Arrays (IRFPA) are increasingly being used for radiometry applications, such as the measurements of spectra at high acquisition rate [1], multispectral and hyperspectral imaging [2], and gas detection in the industrial context [3]. They are also extensively used for military applications including night vision [4], surveillance [5] and ballistic missile defense system [6]. For these systems, it is crucial to control the pixels spectral signature in order to optimize their conception and develop inversion techniques to access spectral information. We describe a modeling approach in the present study, which is adjustable by experimental data, and applicable to the main detector technologies.

One of the most limiting factors of array performance remains disparities in pixels spectral responses. In this paper, what we call "spectral response" refers to the quantum efficiency of the pixel versus the wavenumber of the incident light, in electrons per photon when not normalized. The disparities in pixels spectral responses are illustrated in Fig. 1 which represents the experimental spectral responses of two different pixels as a function of the wavenumber σ. These pixels belong to the same IRFPA, based on mercury-cadmium-telluride (MCT) technology. The response of this detector when illuminated by a homogeneous monochromatic source (for the wavenumber $\sigma = 2047\ \text{cm}^{-1}$) is represented in Fig. 2. As can be seen in these figures, the spectral response differ near the cut-off wavenumbers which can lead to significant errors in the estimated observed radiance, in particular, when the spectrum has a different shape from that of the source used for calibration.

In the present study, we propose an optical model of the structure within the pixel, which enables us to understand and predict these spectral inhomogeneities.

The usual simulation of detector performances is based on semiconductor physics, using energy band diagram, carrier concentration, electric field profile, dark current and quantum efficiency. These parameters are generally optimized as a function of device thickness, applied reverse voltage and operating wavelength, to improve photoelectrical performances [7,8].

Contrary to this description, and rather than developing a purely numerical model approximating the pixel spectral response, our modeling approach is based on optical multilayer formalism. It describes the pixel as a stack of optical layers, characterized by their thicknesses and complex refractive indices. We prove that this optical model is sufficient to accurately predict absorption and interference phenomena inside the pixel, which are responsible for the shape of the spectral response. Optoelectronic conversion and p-n junction are not detailed in this article, as we focus solely on the optical description of the absorption process.

We first describe, in Section 2, an exhaustive model based on a multilayer formalism, which enabled us to derive the pixel spectral response over the total spectral range, using matrix description of the structure. We then propose, in Section 3, a heuristic model which simulates the spectral response over a limited spectral range, using interference phenomena inside the structure, by considering only the most significant waves in terms of amplitude. We prove that this model represents a good approximation of the

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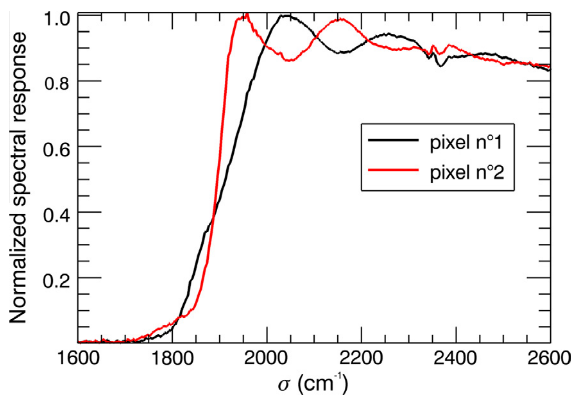

Fig. 1. Experimental spectral responses of two different pixels of a typical MCT IRFPA.

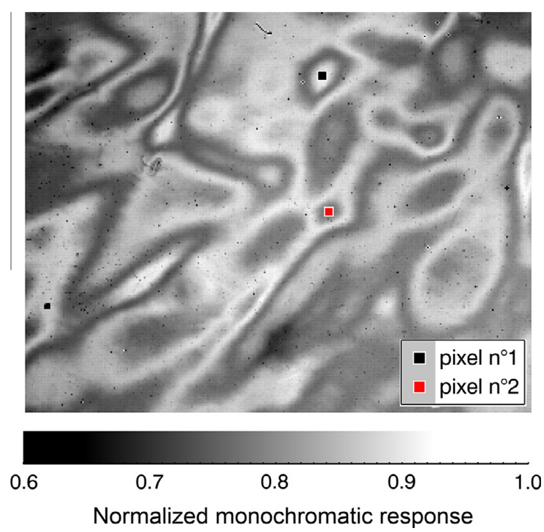

Fig. 2. Experimental monochromatic response of a typical MCT IRFPA (320 × 256 pixels) at wavenumber $\sigma = 2047\ \text{cm}^{-1}$.

exhaustive one over a wide spectral range. Finally, promising comparison with spectral measurements is presented in Sections 4 and 5, thus validating the models. The experimental data used concern two focal plane arrays (FPA) examples in the middle wavelength IR (MWIR) range (3–5 μm) and a major part of the short wavelength IR (SWIR) range (1.5–3 μm). The first one is a wedge substrate detector, whereas the second one is a standard detector.

It has to be noted that, in this article, we focus on standard IR quantum detectors based on MCT, which is the most important material for cooled IR detector applications, owing to the tunable bandgap energy with the cadmium composition. The main advantage of MCT is its high quantum efficiency due to small effective mass, long minority carrier lifetime, and high electron mobility. Nonetheless, this approach can be applied to most of IR sensors designs and materials with slight changes, provided that the optical properties of the structure are known. This includes bulk detectors with material systems like InGaAs [9], superlattices [10], and Quantum-Well Infrared Photodetectors [11], insofar they are described as multilayer structures.

2. Presentation of the exhaustive model

In the following section, we present an exhaustive model describing the optical behavior of an IR pixel. We then go on to relate how this model allows to predict the spectral response of any MCT-like IR detector over the total spectral range. It evaluates the absorbed flux, using the optical properties of the structure in practical operating conditions.

As a general rule, an MCT detector consists in a stack of layers [12]. It is composed of a detection circuit and a CMOS readout circuit, which are electrically connected by indium bumps during the hybridization step [13], as can be seen on Fig. 3(a). The readout circuit is out of interest in our study, as it is not involved in the optical path.

The detection circuit, also referred to as the active layer, is grown over a substrate. It consists in p-n junctions, which represent the absorbent elements of the detector, forming the pixels.

We therefore model a pixel by a stack of optical layers [14,15], as can be seen on Fig. 3(b), where each layer is supposed to be a homogeneous and isotropic dielectric medium. In the following subsection, we describe mathematical formalism for stacked layers, and in Section 2.2, a more detailed description of the different layers constituting an MCT FPA is presented.

2.1. Description of mathematical formalism of stacked optical layers

We remind in this subsection the mathematical formalism characterizing the different flux in a stack of $N-1$ optical layers exposed to an incident plane wave [14,15]. Quantum detectors are sensitive to the number of incident photons which are absorbed, thus generating an electrical signal. This is induced by the photons absorption process that excites the electronic transitions. Supposing that the detector is optimized in terms of quantum efficiency, we can admit that diffusion lengths are comparable to the active layer thickness. Thus, we assume that every electron-hole pair generated by the absorbed photons is collected. This comes down to consider that the quantum efficiency $\eta(\sigma)$ determines the amount of absorption in the structure. Consequently, we determine the spectral response of a pixel $\eta(\sigma)$ to be equal to the absorbed flux $A(\sigma)$.

The pixel spectral response is then derived through the calculation of $A(\sigma)$ using the exhaustive model. Our modeling approach is based on a one-dimensional description of plane waves propagation. As shown in Fig. 4(a), we define the z-axis to be in the direction of the normal to the planes limiting the layers, representing the direction of the propagation. Each layer is assumed to be unbounded in the x- and y-directions. Furthermore, we consider only the normal incidence (propagation in z-direction), as oblique incidence could easily be deduced from this case.

Each layer j is characterized by the thickness d_j, the magnetic permeability μ_j (equal to μ_0, the magnetic permeability of the vacuum), and the complex dielectric constant $\epsilon_j(\sigma)$, depending on the wavenumber σ. The complex refractive index $n_j(\sigma)$ is defined by Eq. (1), where ϵ_0 is the vacuum permittivity, $\eta_j(\sigma)$ the real part

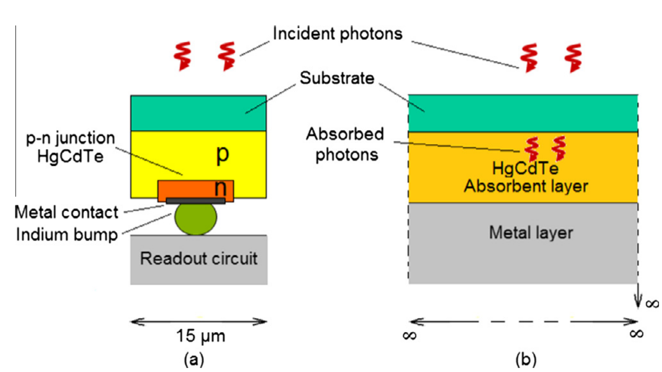

Fig. 3. (a) Diagram of an IR HgCdTe photovoltaic pixel, (b) Diagram of the corresponding optical modeling.

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