One-mode model for patterned metal layers inside integrated color pixels

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Optimized design of the optical filters inside integrated color pixels (ICPs) for complementary metal-oxide semiconductor image sensors requires analytical models. ICP optical filters consist of subwavelength patterned metal layers. We show that a one-mode model, in which subwavelength gaps in the metal layer are described in terms of single-mode waveguides, suffices to predict the salient features of measured ICP wavelength selectivity. The Airy-like transmittance formula, derived for transverse-electric polarization, predicts an angle-independent cutoff wavelength, which is in good agreement with predictions made with a two-dimensional finite-difference time-domain method. © 2004 Optical Society of America

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The materials used in complementary metal-oxide semiconductor (CMOS) technology are chosen to optimize electronic performance. Nevertheless, these materials are also suitable for controlling and detecting optical signals. Current CMOS image sensor technology routinely combines optics and electronics at the micrometer scale. In advanced CMOS technologies feature sizes are reaching the nanometer scale, creating new opportunities for light control. Moving toward this goal, wavelength selectivity was integrated into the image sensor circuit design by application of subwavelength patterns to the metal layers available in a standard CMOS process.[1] We refer to this design as an integrated color pixel (ICP). Specifically, a one-dimensional (1D) patterned metal layer inside an ICP can act as a color filter and can produce wavelength selectivity suitable for color image sensors.[2] An image sensor pixel implemented in 0.18-μm CMOS technology is a complicated structure consisting of up to eight different materials, deposited in as many as 32 layers. In this Letter we show that a one-mode model, in which the subwavelength gaps of a 1D patterned metal layer are described in terms of single-mode waveguides, is in fact sufficient to capture the salient features of the ICP wavelength selectivity, even when the metal layer is modeled as a perfect electric conductor (PEC). For transverse-electric (TE) polarization, when the electric field is polarized parallel to the wires, the model predicts angle-independent wavelength selectivity suitable for wide-angle illumination that is incident upon an image sensor. Given the agreement with measurements, this analytical model should prove useful in optimizing the design of ICPs in CMOS image sensors.

In most CMOS image sensors a color filter array (CFA) provides wavelength selectivity. The CFA is deposited on the sensor surface during separate processing steps and typically consists of a red–green–blue or cyan–magenta–yellow–green pattern [Fig. 1(a)].[3,4] The CFA has been quite successful for CCD imagers, but it has several drawbacks when applied to CMOS image sensors. In 0.18-μm CMOS technology, typical photodetectors are 2–3 μm in size, while the distance between the CFA and the detector can be up to 10 μm. This distance reduces the light-collecting ability of the photodetector,[5] allows color cross talk,[6,7] and imposes stringent design constraints on the microlens array.[8] To alleviate these drawbacks and to integrate optical functionality into the image sensor circuit design we recently prototyped ICPs, using a standard 0.18-μm CMOS technology [Fig. 1(b)]. The optical filters inside the ICP consisted of subwavelength patterned metal layers and exhibited wavelength selectivity in the visible regime (Fig. 2).[1] Electromagnetic field simulations using a two-dimensional (2D) finite-difference time-domain (FDTD) method yielded good agreement with measurements.[2] Measured ICP transmittances are such that a linear combination, e.g., with a 3-by-3 matrix, suffices to produce red, green, and blue color channels with distinct peak sensitivities at approximately 750, 575, and 450 nm, respectively.[1,9] Although first-generation ICPs have a peak transmittance of only 40%, CMOS image sensors in 0.13-μm CMOS technology will permit smaller features and more flexibility in designing suitable patterns. This is expected to result in ICP transmittance comparable to that of CFAs.

To fulfill the promise of ICPs for color and multispectral imaging the design of patterned metal layers needs to be optimized. Analytical models that capture the physical transmission mechanism are essential in guiding the design process. The one-mode model that we present in this Letter provides closed-form Airy-like formulas for the transmittance of the patterned metal layers. Specifically, we derive and discuss the model for TE polarization. The patterned metal layer

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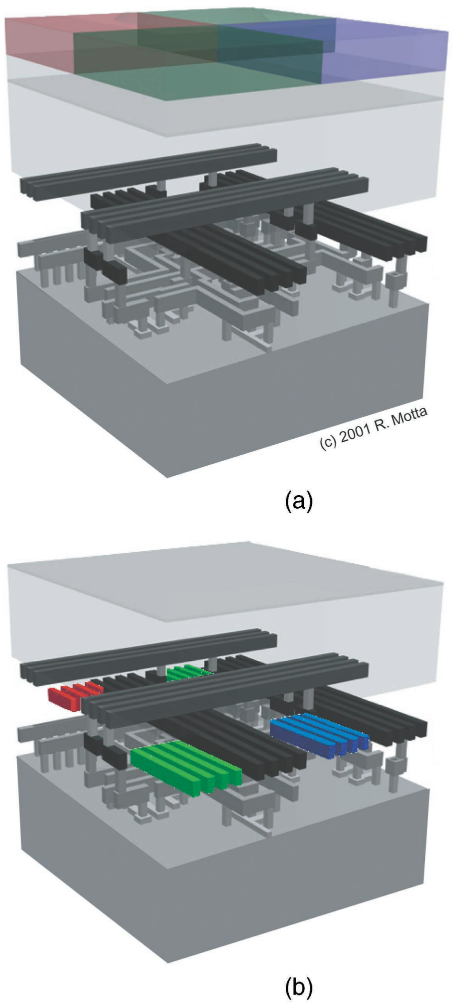

Fig. 1. Geometry of four CMOS image sensor pixels: (a) Conventional arrangement with a red–green–blue color filter array placed on the sensor surface, (b) ICP arrangement that contains patterned metal layers (shown in color) inside the pixel. Used by permission of copyright holder, R. Motta, 2001.

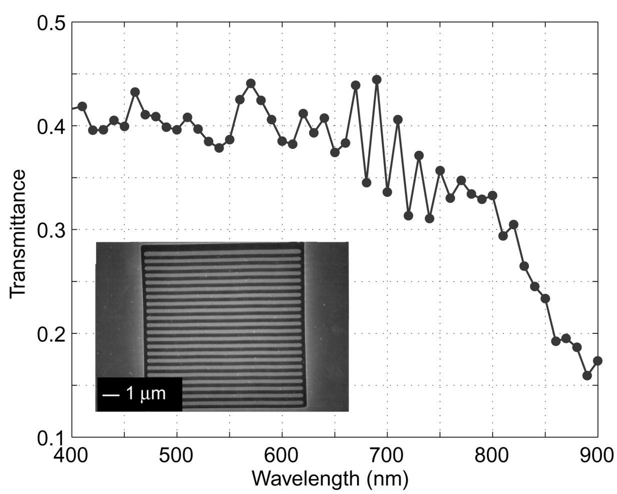

Fig. 2. Measured transmittance of 1D ICPs with a 270-nm gap width designed in 0.18-μm CMOS technology. Measurements are shown for collimated, TE-polarized illumination. Inset, scanning electron micrograph of the ICP patterned metal layers.

geometry is that of a 1D lamellar transmission grating with gap width w, period Λ, and thickness h, embedded in a homogeneous medium with index of refraction n. The wavelength of the incident wave in vacuum is denoted by λ and $k_0 = 2\pi/\lambda$. We also define $\alpha_p = nk_0 \sin(\theta) + pK$, $K = 2\pi/\Lambda$, and $\gamma_p = [1 - (n \sin\theta + pK/k_0)^2/n^2]^{1/2}$. Following a procedure described by Lalanne *et al.*[10] for transverse-magnetic (TM) polarization, we derive an Airy-like formula[11] for the TE transmission coefficient of the qth diffraction order,

$$T_q = \frac{2p_1 u}{-(p_1 - p_2)^2 + (p_1 + p_2)^2 u^2}\,\frac{2\gamma_0 I_{01}{}^* I_{q1}}{\Lambda}, \quad (1)$$

where

$$u = \exp(-jn_{\mathrm{eff}} k_0 h), \quad (2)$$

$$I_{q1} = \begin{cases} -w\pi \dfrac{\exp(j\alpha_q w) + 1}{w^2 {\alpha_q}^2 - \pi^2} & w^2 {\alpha_q}^2 \neq \pi^2 \\ -\dfrac{w}{2j} & w^2 {\alpha_q}^2 = \pi^2 \end{cases}, \quad (3)$$

$$p_1 = \frac{n_{\mathrm{eff}}}{n}\,\frac{w}{2}, \quad (4)$$

$$p_2 = \sum_{p=-\infty}^{\infty} \frac{I_{p1}}{\Lambda}\,\gamma_p I_{p1}{}^*, \quad (5)$$

and n_{eff} is the (complex) effective mode index. If we make the additional assumption that the patterned metal layer can be modeled as a PEC, we have $n_{\mathrm{eff}} = n[1 - (\lambda/2nw)^2]^{1/2}$. The transmittance of the 1D patterned metal layer is obtained by squaring the absolute value of Eq. (1).

The one-mode model, in which the subwavelength gaps of a 1D patterned metal layer are described in terms of single-mode waveguides, is motivated by electromagnetic grating theory.[12] Although the PEC assumption is not crucial, it allows for a simple relationship between the geometrical parameters and the different transmittance regimes of the patterned metal layer for TE polarization. For a PEC layer the boundaries between these regimes are set by the gap width, w, and the refractive index, n. Above $2nw$, TE transmission falls off because of the cutoff of the lowest TE mode in the gaps. Between nw and $2nw$ there is one propagating waveguide mode, and we expect attenuated but approximately constant transmission. Since this range corresponds to the visible wavelength regime for the 1D patterned metal layers in this study, the one-mode model should be applicable. Given $n = 1.46$ for the surrounding medium and measured gap widths of 236 ± 14 nm, the predicted TE fall-off based on the one-mode model is 689 ± 40 nm. This is confirmed by the measurements in Fig. 2, from which we estimate a cutoff wavelength of 677 nm.[2] Given that (a) metals do not behave as PECs in the visible wavelength range, (b) the patterned metal layers are embedded inside the complicated structure of a CMOS image sensor pixel, and (c) the measurements are a mixture of TE and TM signals,[2] it is somewhat

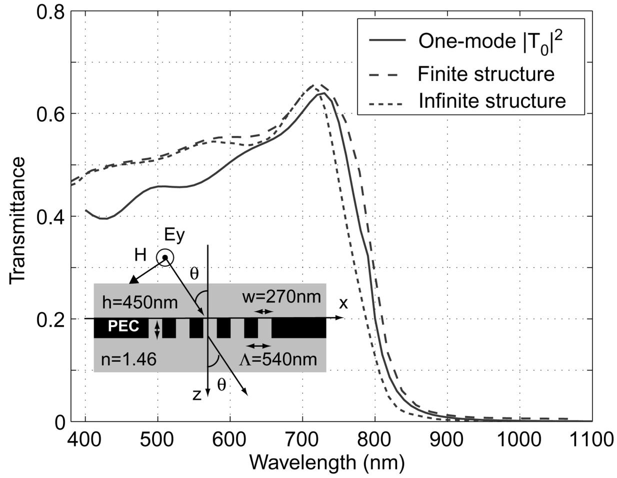

Fig. 3. Transmittance of the patterned metal layer versus wavelength for normally incident TE-polarized light. The one-mode model is compared with 2D FDTD simulations of finite (24-μm-wide simulation domain) and infinite extent in the x direction. Inset, simulation geometry and parameters.

surprising that the one-mode model combined with the PEC assumption still captures the salient features of the transmittance. Furthermore, the model shows that the cutoff wavelength for TE polarization is independent of incidence angle. This is an important feature, since color filters in image sensors are subject to wide-angle illumination from an imaging lens.

Recently, we showed excellent agreement between measured transmittances and transmittances calculated with a finite-difference time-domain (FDTD) approach. In the FDTD simulations we took into account (a) the layered dielectric stack in which the patterned metal layer is embedded inside the CMOS image sensor pixel and (b) a more accurate free-electron Drude model for the metal layer.[2] Although these assumptions improved quantitative agreement, they did not alter the salient features of the transmittance. Therefore we compare the one-mode model with FDTD simulations assuming a homogeneous dielectric surrounding and a PEC metal model. Figure 3 compares the transmittance obtained using the one-mode model with the 2D FDTD simulations for both finite (small pixels) and infinite (large pixels) 1D patterned metal layers. The FDTD simulations were based on a commercially available 2D total-field FDTD implementation.[13] Uniaxial phase-matched layer absorbing boundaries and Bloch-type periodic boundaries truncate the simulation domain in the finite- and infinite-extent cases, respectively.[13] We apply a normally incident pulsed plane-wave excitation centered at 550 nm to obtain the spectral behavior in the visible and the near-infrared wavelength range, using a single FDTD simulation. The incidence plane is chosen above the layer, and the data for determining transmittance are collected behind the layer through direct integration of the Poynting vector.[2] The transmittance is defined as the ratio of the power through a patterned metal layer to the incident power.

The agreement between the one-mode model and both FDTD simulations is very good. The one-mode model correctly predicts the cutoff from 700 to 800 nm but starts to deviate from the FDTD results at smaller wavelengths. This result is attributed to the fact that the higher-order modes become available for transmission in the gaps. Although we do not report on the TM case, we did compare the one-mode model derived by Lalanne *et al.*[10] for TM polarization with 2D FDTD simulations and found very good agreement as well.

In conclusion, we have presented an analytical model for the transmittance of 1D patterned metal layers, which are used as optical filters inside the integrated color pixels of a CMOS image sensor. A one-mode model, in which the metal layer is modeled as a PEC, captures the salient features of the observed wavelength selectivity. This model should therefore prove useful in optimizing the design of ICPs in CMOS image sensors and can also be straightforwardly extended to 2D patterns for polarization-independent color filtering.

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