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Energy transport in lossy resonators by optical admittance methods

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***Abstract*—Improved modeling tools are needed for self-consistent simulation of photon and carrier transport in emerging photonic devices. Here we introduce the method of optical admittances to simplify the calculation of Green's functions and interference effects of energy transport in the recently introduced quantized fluctuational electrodynamics framework. Our approach enables a straightforward analytical method to calculate e.g. the local and nonlocal densities of states in photonic resonators. Furthermore, the resulting wave-optical treatment of emission enhancement and photon recycling can be coupled with drift-diffusion simulations using the so-called interference-exact radiative transfer equations to provide a full-device model of optical and electrical energy transport in arbitrary multilayer structures. We expect the presented framework to enable detailed new studies of emerging photonic devices based on e.g. thin-film technology.**

I. INTRODUCTION

Photonic technologies have disrupted many areas of the society, such as energy production through photovoltaic cells and general lighting through high-efficiency LEDs [1, 2]. As conventional LEDs and solar cells are becoming commoditized, research is being geared towards more sophisticated applications from emerging materials and nanostructures. Examples of this include electroluminescent cooling [3], optical on-chip communication using nanostructure optical interconnects [4], photocatalytic solar fuel production [5], and various nanowire-based devices [6]. However, to speed up the development of new nanophotonic devices, accessible modeling tools are needed where electrical and wave-optical effects are self-consistently coupled. In pursuit of creating such generic fully optoelectronic modeling tools, here we implement the recently introduced quantized fluctuational electrodynamics (QFED) [7] using the so-called optical admittance functions [8].

Admittances and the closely related Smith charts are widely used in electrical engineering to solve wave equations in the field of transmission line theory. Considering their apparent convenience in solving wave equations, it is even somewhat surprising that admittances have not been adopted more widely in wave optics. The optical admittances can be solved analytically for arbitrary piecewise homogeneous structures and selected other special cases, and numerically for structures with material gradings. We show that they also enable expressing the dyadic Green's functions as straightforward integral equations of the admittances. Furthermore, we use optical admittances to implement the interference-exact radiative transfer equations (IFRTEs) [9], which can be readily combined with the drift-diffusion model to create a fully self-consistent model of photon and carrier transport.

II. THEORY

Optical admittances describe the propagation of electromagnetic fields in arbitrary planar devices, and their differential equations are presented e.g. in Ref. 8. For arbitrary relative permittivity and permeability ε and μ, the optical admittance for TE and TM modes can be solved from

$$\frac{d\gamma^{TE}(z)}{dz} = ik_0\mu\left[\gamma^{TE}(z)^2 - \kappa^{TE}(z)^2\right], \tag{1}$$

$$\frac{d\gamma^{TM}(z)}{dz} = ik_0\varepsilon\left[\gamma^{TM}(z)^2/\kappa^{TM}(z)^2 - 1\right], \tag{2}$$

where $\kappa^{TE}(z) = -\sqrt{\varepsilon\mu - K^2/k_0^2}/\mu$ and $\kappa^{TM}(z) = -\varepsilon/\sqrt{\varepsilon\mu - K^2/k_0^2}$, K being the lateral component of the k vector. These equations can be solved analytically for piecewise constant ε and μ. Once the admittances are known, it becomes straightforward to express many otherwise complicated formulas in the QFED in a simple form. As an example, the optical admittances can be used to express the local densities of states (LDOSs) as

$$\rho_e(z,K,k_0) = \frac{-1}{4\pi^3 c}\Re\left\{\left(\frac{1}{\gamma_r^{TE}+\gamma_l^{TE}} + \frac{1}{\gamma_r^{TM}+\gamma_l^{TM}} + \frac{(K/k_0)^2}{|\varepsilon|^2}\frac{\gamma_r^{TM}\gamma_l^{TM}}{\gamma_r^{TM}+\gamma_l^{TM}}\right)\right\} \tag{3}$$

for the electric field and

$$\rho_m(z,K,k_0) = \frac{-1}{4\pi^3 c}\Re\left\{\left(\frac{\gamma_r^{TM}\gamma_l^{TM}}{\gamma_r^{TM}+\gamma_l^{TM}} + \frac{\gamma_r^{TE}\gamma_l^{TE}}{\gamma_r^{TE}+\gamma_l^{TE}} + \frac{(K/k_0)^2}{|\mu|^2}\frac{1}{\gamma_r^{TE}+\gamma_l^{TE}}\right)\right\} \tag{4}$$

for the magnetic field, where $\gamma_r^{TE,TM}$ and $\gamma_l^{TE,TM}$ are the optical admittances calculated for rightward and leftward modes. Furthermore, the admittances enable expressing all the spectral dyadic Green's functions as straightforward integral equations with help of Refs. 9, 10. The dyadic Green's functions can then be used to calculate all the nonlocal densities of states (NLDOSs) required in the QFED, and the interference-exact damping and scattering coefficients required in the IFRTE [9].

III. RESULTS AND DISCUSSION

To shortly illustrate how the optical admittance method can be used to account for wave-optical effects in photon emission and photon recycling, we calculate the LDOSs and NLDOSs in an example GaN-based quantum well (QW) light emitter. We assume that the structure is grown on a native n-type GaN substrate and has a 3 nm thick InGaN QW, a 150 nm thick p-type GaN layer, and a 20 nm thick metal contact before its outer interface with air. The emission wavelength is 445 nm in the simulations, corresponding to photon energy 2.786 eV. The relative permeability is 1 everywhere, and the refractive index is 2.51+0.0029i (GaN), 2.51+2.094i (InGaN), 0.013+3.119i (metal contact) and 1 (air).

Figure 1(a) shows the total electromagnetic LDOS as a function of position and lateral k vector calculated using optical admittances. The dashed lines mark the positions and K values of interest as explained in the caption. It can be seen that in the light cone of air ($K/k_0 < 1$), the LDOS is constant within the GaN and air regions, except for the largest values of K/k_0. In the light cones of GaN ($1 < K/k_0 < 2.51$), there is an interference pattern in the GaN side due to the total internal reflection at the outer surface, as well as an evanescent wave in air. Additionally, there is a plasmon resonance in the air side slightly above $K/k_0 = 1$, exhibited as an elevated LDOS. Above $K/k_0 = 2.51$, only evanescent modes are present as K is larger than the total k vector in GaN.

The total electromagnetic NLDOS divided by LDOS is shown in Fig. 1(b), and it is calculated by placing the source point in the middle of the InGaN QW. At K/k_0, the NLDOS/LDOS value is larger in air than in GaN, indicating that the structure and QW position are not optimal for flip-chip operation where light is extracted from the substrate side on the left. The interference pattern seen in the LDOS in Fig. 1(a) at $1 < K/k_0 < 2.51$ can be seen also in Fig. 1(b) for light emission towards the substrate. The results in Fig. 1 illustrate that with the present device, the method could be used e.g. to investigate how the QW position affects the emission towards different K/k_0 values.

Outlook: Using the equations from Ref. 9, position-dependent absorption and scattering coefficients can be obtained for the IFRTE from the optical admittances. In our work we couple the resulting IFRTE with drift-diffusion simulations of carrier transport to perform fully self-consistent modeling of energy transport in the double-diode structures of Ref. 3, aiming to optimize them for electroluminescent cooling.

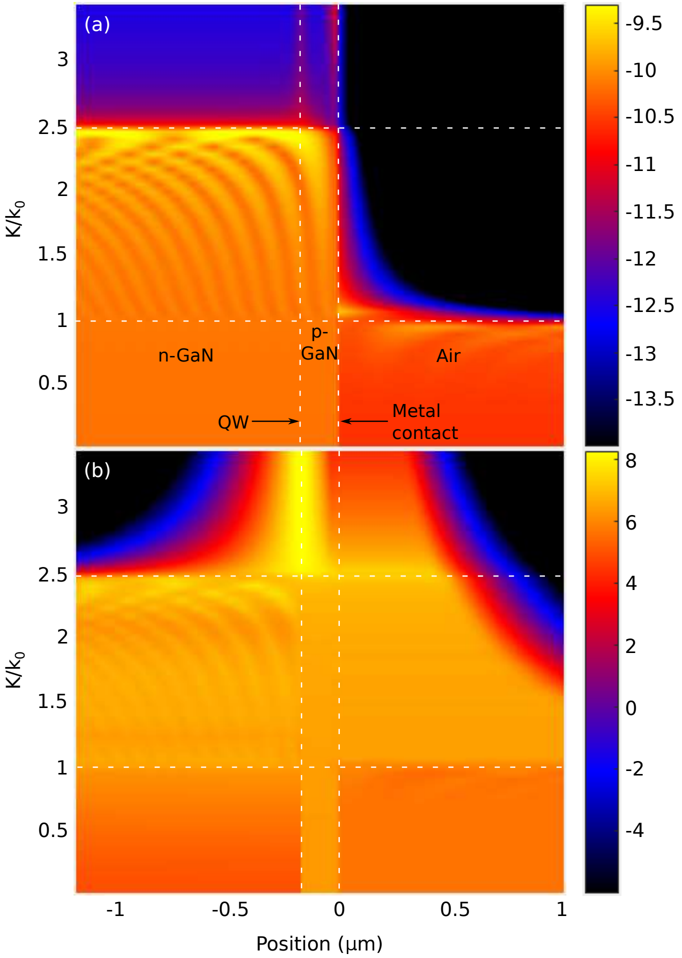

Fig. 1. Total electromagnetic (a) LDOS and (b) NLDOS/LDOS in the GaN QW LED structure as a function of position and the lateral k vector. In (b), the source point is in the middle of the QW. The horizontal dashed lines mark the light cones of air and GaN, and the vertical lines mark the positions of the QW and the contact-air interface.

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