Concept of an Optical Leaky-Wave Antenna Embedded in a Fabry-Pérot Resonator

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***Abstract*—We investigate the radiation of an optical leaky-wave antenna embedded in a Fabry-Pérot resonator (FPR), resonating in the direction of the guided leaky wave. Leaky-wave radiation is achieved via the generation of a −1 Floquet harmonic in a dielectric waveguide due to the inclusion of a periodic set of perturbations. The FPR is formed by confining the dielectric waveguide and the leaky-wave section between two partially reflective mirrors. We report the design principles that are required to achieve a pencil beam at broadside as a superposition of leaky waves that travel inside the FPR in two opposite directions. We also investigate the tunability of the radiation by using semiconductor regions in the waveguide and thereby exciting and controlling excess carriers. We report simulation results related to a realistic design as a proof of the concept.**

I. INTRODUCTION

In this paper we characterize the enhanced tunability of radiation level of an optical leaky wave antenna (OLWA) integrated inside a Fabry-Pérot resonator (FPR). Due to the (constructive/destructive) interference of two leaky waves (LWs) traveling in opposite directions with the same wavenumber inside the resonator, this composite OLWA provides flexibility in radiation control. Indeed, the resonance of the FPR combined with the interference mechanism of the far fields of the two LWs leads to an ample range of parameters that can be optimized to tailor the far field and to improve the tunability. Moreover, a high quality factor of the FPR enables high level modulation of the far field through excess carrier injection in the semiconductor waveguide. The ability to control the interaction of optical antennas and the environment can improve the performance of devices such as light-emitting diodes, lasers and solar cells, and bio-chemical sensors [1]-[3]. The design of an OLWA made of a silicon nitride waveguide comprising periodic semiconductor (silicon) perturbations, capable of producing narrow beam radiation has been introduced in [4]. The electronic/optical tunability for refractive index and absorption coefficient of silicon perturbations in [5] proved that the control on the radiation of an isolated OLWA was rather limited. That is why in [5] the use of an OLWA integrated inside a FPR has been proposed for the first time as a possible solution to enhance the radiation control at a fixed direction. However, the OLWA inside the FPR is rather a complex electromagnetic system and requires some analytic investigation as reported in this paper. This analysis also leads to design rules for such a composite antenna. Similar principles can be applied also to LW antennas inside FPRs at microwave frequencies.

II. RADIATION FROM AN OLWA INSIDE FPR

The radiation from an OLWA is based on the excitation of a LW guided mode with complex wavenumber $k_{\mathrm{LW}} = \beta_{\mathrm{LW}} + i\alpha_{\mathrm{LW}}$. LW exponential decay is caused by radiation. The use of LWs for the generation of narrow beam radiation is a well-known technique [4]-[9], and more details on the development of leaky-wave antennas can be found in [10]. The schematic of the OLWA inside the FPR considered in this paper is provided in Fig. 1. The antenna comprises a waveguide composed of three sections within two highly reflective mirrors that make up the FPR along the propagation direction of the LW. The central part is the LW section (with length L) from which radiation takes place, whereas the other two waveguide sections (with lengths D_1 and D_2) host only the bound modes (non-radiative) with wavenumber k_{WG}. Here we assume the wave is injected through mirror 1, single-mode operation, and negligible reflection at the interface of the leaky and non-leaky waveguide sections.

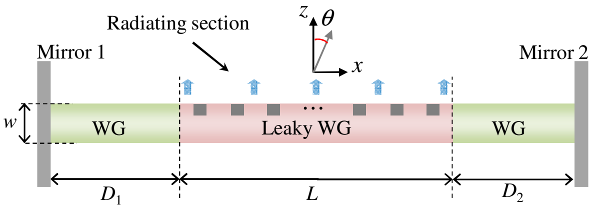

Figure 1. The schematic of the OLWA inside the FPR, where the leaky −1 Floquet harmonic is generated using periodic perturbations (WG: waveguide).

The radiated far field from the leaky waveguide can be expressed as

$$F^{\mathrm{T}}(\theta) = \left[F^{+}(\theta) + \Gamma_0 F^{-}(\theta)\right] f_{\mathrm{FPR}} \tag{1}$$

where $F^{\pm}$ denote the far-field patterns due to the LWs propagating along the + and – x directions, Γ_0 is the reflection coefficient toward the + x direction referred to the origin

($x=0$, defined as the center of the leaky section), and f_{FPR} is a coefficient determined only by the resonator parameters. The individual far-field pattern terms in (1) are given by

$$F^{\pm}(\theta)=\cos\theta\frac{\sin\left[\left(k_0\sin\theta\mp k_{\mathrm{LW}}\right)L/2\right]}{\left(k_0\sin\theta\mp k_{\mathrm{LW}}\right)L/2}, \qquad (2)$$

which define the radiation patterns of LWs propagating with wavenumber $\pm k_{\mathrm{LW}}$, and k_0 is the wavenumber in free space (the surrounding medium). Note that in (1) the pattern due to the LW propagating along the $-x$ direction is scaled by $\Gamma_0=\Gamma_2 e^{ik_{\mathrm{LW}}L}e^{ik_{\mathrm{WG}}2D_2}$, where Γ_2 is the reflection coefficient of mirror 2. Thus, the radiation pattern at any direction can be tuned for constructive interference by selecting an appropriate value of D_2 . Our aim is to have a single beam at broadside; therefore, we enforce that the total far field at $\theta=0°$ is larger than the individual LW beams' peaks at $\theta_{\mathrm{LW}}^{\pm}=\sin^{-1}\left[\pm\beta_{\mathrm{LW}}/k_0\right]$, as sketched in Fig. 2. This condition is satisfied when

$$\frac{\left|\operatorname{sinc}\left(\frac{1}{2}Lk_{\mathrm{LW}}\right)\right|}{\operatorname{sinhc}\left(\frac{1}{2}L\alpha_{\mathrm{LW}}\right)}\left[1+\left|\Gamma_2\right|e^{-\alpha_{\mathrm{LW}}L}\right]>1. \qquad (3)$$

In addition to the beam tailoring described in Fig. 2, we can also tune the resonance of the FPR by maximizing the magnitude of

$$f_{\mathrm{FPR}}=\left[1-\Gamma_1\Gamma_2 e^{ik_{\mathrm{LW}}2L}e^{ik_{\mathrm{WG}}2\left(D_1+D_2\right)}\right]^{-1}, \qquad (4)$$

where Γ_1 is the reflection coefficient of mirror 1. Note that D_1 allows tuning the resonance without modifying the radiation pattern, and this is an advantage of the OLWA inside the FPR for it provides several degrees of freedom in the design.

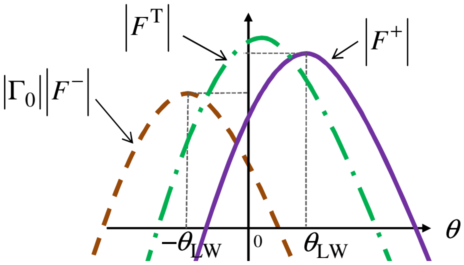

Figure 2. Sketch of the interfering far-field beams due to the waves propagating in the + and – x directions (solid purple and dashed brown, respectively), and of the total far-field pattern (dash-dotted green).

Moreover, by modifying the complex refractive index of the semiconductor regions of the waveguide through excess carrier injection, the resonance parameter f_{FPR} may be dramatically changed when the resonance has a large quality factor. In Fig. 3 we provide an example of how the radiation level of the broadside beam of an antenna design satisfying (3) can be tuned through excess carrier generation. We consider a silicon (Si) waveguide sandwiched between two silica domains and vacuum-filled perturbations. The design parameters (lengths in μm) are as follows: $D_1=0.15$, $D_2=0.35$, $L=5.52$ $w=0.7$, $\Gamma_1=0.919\measuredangle-142°$, $\Gamma_2=0.994\measuredangle-148°$. The Si refractive index modification with respect to the excess carrier concentration of electrons and holes $N_{e,h}$ is estimated by using the formulas provided in [5]. The radiation pattern modulation at 193.4 THz by varying the excess carrier concentration is plotted in Fig. 3 obtained by full-wave simulations in COMSOL Multiphysics (a commercial finite-element solver). We report 5.4 dB broadside beam level control as an initial result. Further optimization may lead to control as large as 10 dB.

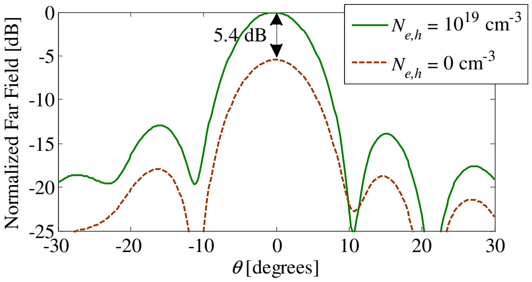

Figure 3. Control of the far-field radiation pattern of the OLWA inside FPR, with presence and absence of excess carriers in the Si regions.

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