Enhancing radiation control of an optical leaky wave antenna in a resonator

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ABSTRACT

We analyze the theoretical and physical properties of a CMOS compatible optical leaky wave antenna (OLWA) integrated into a Fabry-Pérot resonator (FPR) at 193.4 THz (wavelength $\lambda_0 = 1550$ nm). The presented OLWA design is composed of a silicon (Si) dielectric waveguide sandwiched between two silica glass (SiO₂) domains, and it comprises periodic perturbations (cavities of vacuum). We first describe the radiation of the isolated OLWA whose radiation pattern is due to the excitation of a leaky wave, slowly decaying while traveling. The perturbations are indeed designed to obtain a leaky wave harmonic with very low attenuation and phase constants. Then, we integrate the same OLWA into a FPR where two leaky waves with the same wavenumber are travelling in opposite directions inside the resonator. We show that the radiation level at the broadside direction can be effectively controlled by modifying the optical properties of the Si waveguide through electron-hole excess carrier generation (found to be highly enhanced when it is integrated into a FPR). The design of the integrated OLWA is properly set to guarantee the constructive interference of the two radiated beams provided by the two leaky waves in the FPR. The modal propagation constant in the integrated OLWA can be then altered through excess carrier generation in Si, thus the antenna can be tuned in and out of the resonance thanks to the high FPR quality factor, and the LW modal dispersion relation. This allows for enhanced radiation level control at broadside, and preliminary results show up to 13 dB beam modulation.

Keywords: optical leaky wave antenna (OLWA), Fabry-Perot resonator, CMOS compatible, subwavelength structures, waveguides, silicon on insulator (SOI), electronic tunability.

1. INTRODUCTION AND STATEMENT OF THE PROBLEM

Optical antennas transmit (receive) light waves into (from) the surrounding space and have the potential to boost the efficiency of optoelectronic devices such as light-emitting diodes, lasers and solar cells, and bio-chemical sensors [1-3]. A particular kind of optical antennas is an optical leaky wave antenna (OLWA) whose working principle is based on the excitation of a leaky wave (LW) guided mode, which is a guided wave that radiates power as it propagates with wavenumber $k_{LW} = \beta_{LW} + i\alpha_{LW}$ in the guiding structure, exponentially decaying while propagating. The subject of LWs has been largely studied in the past, including their role in producing narrow beam radiation [4-7], and the reader is addressed to [8] for a review on recent developments on LWs.

We have recently introduced in [9] the design of a dielectric (silicon nitride) OLWA with periodic semiconductor (silicon) perturbations, capable of producing narrow beam radiation very close to the normal direction (the +z direction in Fig. 1, also called the broadside direction in the antenna community), with electronic or optical tuning capability. The use of silicon offers the electronic/optical tunability for optical parameters of silicon (such as refractive index and absorption coefficient) via excess carrier injection. Nevertheless, we have observed in [10, 11] that the control on the radiation on an isolated OLWA was rather limited. This limitation can been overcome by integrating the OLWA inside a resonator to enhance and achieve a radiation control at a fixed direction that would pave the way to very fast optical switches, as an example.

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The aim of this paper is to investigate the enhanced radiation level control of a leaky wave antenna integrated inside a FPR. The radiated far field of such an antenna is the result of an (constructive/destructive) interference of the leaky waves traveling in opposite directions with the same wavenumber inside the resonator. Given that the leaky waves propagate with a very small attenuation constant, a sharp resonance of the FPR with a high quality factor enables high level modulation of the far field through excess carrier injection.

The structure of the paper is as follows. The structure of the OLWA is explained and the radiation control capability through excess carrier injection is demonstrated in Sec. 2. Then the OLWA is embedded into a Fabry-Perot resonator (FPR) in Sec. 3, where the leaky waves' resonance inside the FPR is theoretically modeled to show its radiation level modulation through excess carrier injection. We also provide simulation results proving the radiation pattern tunability.

2. CONTROL OF RADIATION OF AN ISOLATED OLWA

The schematic of an isolated OLWA is shown in Fig. 1. It comprises of a silicon waveguide (WG) with width $w = 0.7 \,\mu\text{m}$ sandwiched between two silica (SiO₂) domains with width $W = 5 \,\mu\text{m}$ (different widths would not results in different working principles and results.) The antenna is surrounded by free space. A guided wave with wavenumber k_{WG} , polarized along y, is injected from the left side of the antenna (with guided wavelength of 461.3 nm at 193.4 THz) which transitions into a leaky wave as it enters into the periodically perturbed section. The leaky waveguide comprises a periodic set of N = 50 perturbations, with dimensions $h = 120 \,\text{nm}$ and $l = 120 \,\text{nm}$ and period $d = 460 \,\text{nm}$, which is set close to the guided wavelength in order to radiate at the broadside direction (the +z direction in Fig. 1). The details of the design procedure, reported in [9], are not repeated here for brevity.



Fig. 1. Schematic of an isolated OLWA, with dimensions.

When the guided wave encounters the periodic silicon perturbations, it transitions into a leaky wave (LW), with radiating Floquet harmonic with wavenumber $k_{LW} = \beta_{LW} + i\alpha_{LW}$, slowly decaying while traveling along the waveguide. Such a mode decays exponentially along the structure, even for a lossless structure, and a leakage phenomenon (radiation) takes place. In detail, the *y*-component of the guided electric field satisfies the quasi-periodic property, for which the electric field at any place along the periodic structure can be represented as the superposition of Floquet spatial harmonics

$$E(x, y) = \sum_{n = -\infty}^{\infty} E_n(y) e^{ik_{x,n}x}, \qquad k_{x,n} = \beta_{x,0} + 2n\pi/d, \qquad (1)$$

where $\beta_{x,0}$ is the fundamental wavenumber of the wave propagating along the perturbed waveguide, $k_{x,n}$ is the Floquet wavenumber, *n* is its order, and $E_n(z)$ is the weight of the *n*-th harmonic [12-14]. The purpose of the periodic perturbations is to create a radiating n = -1 harmonic. Its wavenumber is

$$k_{x,-1} = k_{\text{LW}} = \beta_{\text{LW}} + i\alpha_{\text{LW}}, \quad \text{with} \quad \beta_{\text{LW}} = \beta_{x,0} - 2\pi/d, \quad (2)$$

such that $-k_0 < \beta_{LW} < k_0$, where $k_0 = 2\pi / \lambda_0$ is the free-space wavenumber. The radiated beam's directivity and pointing angle depend strictly on β_{LW} and α_{LW} , thus it is possible to control the radiated field by modifying the refractive index of the waveguide material: silicon. In this paper we focus on the resulting modulation of radiated far-field at broadside.

The use of silicon and silicon on insulator (SOI) technology provides opportunities for opto-electronic integration. As an indirect bandgap material, silicon is highly transparent for optical communication wavelengths. The use of free carrier plasma dispersion effect [15] can induce changes in refractive index and absorption coefficient, which are two critical parameters in OLWA radiation pattern.

From previous analyses [9], we know that the radiation pattern highly depends on the attenuation coefficient of the antenna and the effective index. By generating excess carrier density of both electrons and holes in Si can alter both the real and imaginary parts of its refractive index (unitless) as described by the Drude model [16, 17]

$$\Delta n_{Si} \left(N_e, N_h \right) = -\left(8.8 \times 10^{-4} N_e + 8.5 N_h^{0.8} \right) \times 10^{-18}, \qquad \Delta k_{Si} \left(N_e, N_h \right) = \frac{\left(8.5 N_e + 6.0 N_h \right) \times 10^{-10}}{k_0}, \tag{3}$$

where N_e and N_h are the concentrations of electrons and holes (expressed in cm⁻³) in Si, and k_0 is the free space wavenumber (expressed in m⁻¹). The variation in the Si refractive index modifies the leaky wave constant $k_{I,W} = \beta_{I,W} + i\alpha_{I,W}$ and thus alters the far-field radiation pattern.

In Fig. 2, we report the radiation pattern of the OLWA comprising 50 periodic perturbations without excess carriers in Si domain (with $n_{\rm Si} = 3.48$, blue solid curve). We also report the pattern when excess electrons and holes with the concentration $N_e = N_h = 10^{19}$ cm⁻³ are introduced in the same Si domain (leading to a complex $n_{\rm Si} \approx 3.458 + i0.004$, dashed red curve). Note that the patterns are normalized with respect to the maximum of the case without excess carriers. The radiated field is very directive and points close to broadside ($\theta \approx 0^\circ$) and the variation of the antenna's realized gain through excess carrier injection is limited to about 1.3 dB. Since we aim at achieving much larger radiation control, we propose the integration of the OLWA into a FPR, as explained in the next Section.



Fig. 2. Radiation pattern in the *x*-*z* plane of an isolated OLWA with and without excess carriers in Si, obtained by full wave simulations (using COMSOL Multiphysics, a commercial finite element method solver).

3. CONTROL OF RADIATION OF AN OLWA INTEGRATED INTO A FABRY-PEROT RESONATOR

The schematic of the proposed structure is shown in Fig. 3. It comprises a WG made of three regions within two highly reflective mirrors (which form a FPR configuration along the propagation direction of the leaky wave). The two mirrors have width $H = 4.8 \,\mu\text{m}$ and lengths $l_1 = 20 \,\text{nm}$ (mirror 1) and $l_2 = 150 \,\text{nm}$ (mirror 2). The central leaky region (i.e., the OLWA) of length Nd (centered about x = 0) provides the radiation. The radiating region is implemented in the 2D model in Fig. 3 as a periodic set of N = 12 perturbations; all other dimensions are as in Sec 2. On either side of the leaky region there are non-radiating WG regions of lengths $D_1 = 130 \,\text{nm}$ and $D_2 = 120 \,\text{nm}$ which are important in the determination of the FPR resonance condition as described in the following; moreover D_2 is important for the (constructive /destructive) interference of the radiation from the two LWs.



Fig. 3. Schematic of an OLWA embedded into a Fabry-Perot resonator and a possible implementation (2D model) made of a silicon waveguide sandwiched between silica glass domains.

Assume now that the wave component propagating in the +x direction that reaches the center of the leaky region (i.e., x = 0 in Fig. 3) is defined as E_0 . The total field inside the resonators is due to multiple reflections from mirrors 1 and 2 (Fig. 3). The wave propagating in the +x direction after one round trip inside the resonator has a factor given by $\Gamma_1\Gamma_2 e^{ik_{\rm LW}2L}e^{ik_{\rm WG}2(D_1+D_2)}$, where $\Gamma_1 = 0.919 \measuredangle -142^\circ$ and $\Gamma_2 = 0.994 \measuredangle -148^\circ$ are the reflection coefficients of mirrors 1 and 2. The total LW field propagating in the +x direction inside the leaky region is then given by the superposition of the multiple reflections as

$$E^{+}(x) = E_{0}e^{ik_{\mathrm{LW}x}}\sum_{m=0}^{+\infty} \left[\Gamma_{1}\Gamma_{2}e^{ik_{\mathrm{LW}}2L}e^{ik_{\mathrm{WG}}2(D_{1}+D_{2})}\right]^{m}$$
(4)

with m an index indicating the number of round trips. Expression (3) can be rewritten as

$$E^{+}(x) = f_{\text{FPR}} E_0 e^{ik_{\text{LW}}x}, \quad f_{\text{FPR}} = \frac{1}{1 - \Gamma_1 \Gamma_2 e^{ik_{\text{LW}}2L} e^{ik_{\text{WG}}2(D_1 + D_2)}}.$$
(5)

where f_{FPR} accounts for the multiple reflections inside the resonator. The resonance condition may be expressed as the maxima of $|f_{\text{FPR}}|$, which in turn is given as

$$\angle \Gamma_1 + \angle \Gamma_2 + \beta_{\text{LW}} 2L + k_{\text{WG}} 2(D_1 + D_2) = 2r\pi \quad \text{where } r \text{ is an integer.}$$
(6)

Given that the condition in (6) is satisfied, the value of $|f_{\text{FPR}}|$ is

$$|f_{\rm FPR}| = \frac{1}{1 - |\Gamma_1 \Gamma_2| e^{-\alpha_{\rm LW} 2L}}.$$
 (7)

It is clear from (7) that the reflection coefficients of the mirrors should be close to 1 in magnitude and that the leaky wave's attenuation, determined by the factor $\exp(-\alpha_{LW} 2L)$, should be adjusted properly in order to design the antenna with a sharp resonance which would enable us to control the radiation efficiently. For our design, and the attenuation constant is very small, one can infer that from the very directive radiation in Fig. 2. The slowly decaying wave implicitly imposes an upper limit on the number of perturbations (i.e., the attenuation along the leaky section should be very low, and in turn $\exp(-\alpha_{LW} 2L)$ should be close to 1) that can be used to achieve a large resonance quality factor. Note that the length $D_1 + D_2$ has no impact on the resonance enhancement $|f_{FPR}|$, in contrast it can be used for tuning the resonance. Similarly, the total LW field propagating in the -x direction, accounting for all reflections, is given in terms of E_0 and $\Gamma_0 = \Gamma_2 e^{ik_{LW}L} e^{ik_{WG} 2D_2}$, the reflection coefficient towards the +x direction referred to the center x = 0, as

$$E^{-}(x) = f_{\text{FPR}} \Gamma_0 E_0 e^{-ik_{\text{LW}}x}.$$
(8)

Equations (4) and (8) are valid for x between -Nd/2 and Nd/2, where the two waves are leaky. Each LW will provide far field beams that depend on the leaky wave wavenumber k_{LW} , as well as on the resonator parameter f_{FPR} (large at the resonance), which can be used for modulating the magnitude of the far field. By using the equivalent aperture technique [5, 9, 18] over the contour from where we assume radiation is occurring (e.g., here defined by the dashed red contour in Fig. 3), the far zone field due to the two leaky waves in the $\pm x$ direction are found as

$$E_{\rm FF}^{+}(\rho,\theta) = F^{+}(\theta) f_{\rm FPR} E_0 e^{-i\frac{\pi}{4}} \sqrt{\frac{k_0}{2\pi}} N d \frac{e^{ik_0\rho}}{\sqrt{\rho}},$$

$$E_{\rm FF}^{-}(\rho,\theta) = \Gamma_0 F^{-}(\theta) f_{\rm FPR} E_0 e^{-i\frac{\pi}{4}} \sqrt{\frac{k_0}{2\pi}} N d \frac{e^{ik_0\rho}}{\sqrt{\rho}}$$
(9)

where ρ is the distance from the antenna center on the x-z plane and the far-field pattern is

$$F^{\pm}(\theta) = \cos\theta \frac{\sin\psi^{\pm}(\theta)}{\psi^{\pm}(\theta)}, \quad \psi^{\pm}(\theta) = (k_0 \sin\theta \mp k_{\rm LW}) Nd / 2.$$
(10)

The the total far field, produced by both LWs, is then given by

$$E_{\rm FF}^{\rm TOT}\left(\rho,\theta\right) = \left[F^{+}\left(\theta\right) + \Gamma_{0}F^{-}\left(\theta\right)\right]f_{\rm FPR}E_{0}e^{-i\frac{\pi}{4}}\sqrt{\frac{k_{0}}{2\pi}}Nd\frac{e^{ik_{0}\rho}}{\sqrt{\rho}}\tag{11}$$

From (11), it is straightforward to observe that one can tune the beams to constructively interfere at broadside.

In Fig. 4, we plot the far-field patterns of an OLWA with 12 perturbations integrated into a FPR, for two cases: (i) without and (ii) with excess carriers inside the Si domain in between the mirrors. In case (i), the antenna is tuned to resonance; whereas in case (ii) the antenna falls out of resonance due to the presence of excess carriers. A 13 dB level variation is observed, which is a much larger value than the 1.3 dB level modulation achieved without the resonator in Fig. 2. However this comes with the cost of a bigger half-power beam width, because a less attenuated wave (resulting in a smaller radiating section) is necessary to achieve a high FPR quality factor.

In Fig. 5, the magnitude of the electric field phasor is reported for the cases without and with excess carries in the Si region of the FPR. Apparently, when the FPR is resonating the radiated field is also enhanced due to the resonance. Upon the variation of the refractive index of Si through excess carrier generation, the FPR falls out of resonance, so the field inside the resonator and the radiated far field sharply decreases. This enhanced control of radiation from the OLWA inside the FPR paves the way for innovative fast optical switches.



Fig. 4. As in Fig. 2, for an OLWA integrated into a FPR. Note the large variation of the radiated field when introducing excess carriers.



Fig. 5. The electric field map ($|\mathbf{E}(\mathbf{r},\omega)|$) on the antenna (a) when there are no excess carriers in Si domain between the mirrors, and the antenna is operating at resonance, and (b) upon the generation of excess carriers in Si, the antenna is falling out of resonance, resulting in a sharp decrease of the field intensity inside the FPR. The incident power on the port is 10 kW/m.

4. CONCLUSION

We have shown the radiation performance at 193 THz of (i) an isolated OLWA, and (ii) and OLWA embedded into a resonator. Moreover, we have shown the control on the radiation level at a fixed direction, achieving up to 13 dB variation for an OLWA integrated into a FPR, opening up possibilities for the design of fast optical switches or sensors.

We have shown here only the radiating performance. However, by reciprocity, the same large variation of detected power would be achieved when the antenna is working in the receiving mode.

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