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Radiation Properties of an Integrated Optical Leaky Wave Antenna with Periodic Silicon Perturbations

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***Abstract*—We propose a highly directive optical leaky wave antenna (OLWA) radiating at 1550 nm composed of a dielectric waveguide comprising periodic silicon (Si) perturbations. The antenna working principle is based on the excitation of a leaky wave guided mode in the perturbed waveguide. Here we study the radiation properties for two sets of perturbation dimensions, and show beam scanning capabilities of the antenna (radiation level and direction) at broadside by varying the free space wavelength. Moreover, the use of Si offers the electronic/optical tunability of its complex refractive index by excess electron-hole carrier density generation via current injection (electronic control) or optical absorption (optical control). Therefore, by changing the Si refractive index we vary the leaky wave attenuation constant and the input impedance of the antenna, which in turn allow for beam control capabilities.**

I. Introduction

An optical leaky wave antenna (OLWA) is a device that radiates a light wave into the surrounding space from a leaky wave (LW, [1-3]) guided mode. By reciprocity, the same device also couples efficiently the receiving optical power from a specific direction into a guided optical mode. Very directive near-IR optical antennas with controlled beam steering and radiation pattern capabilities are desired for applications such as planar imaging and LIDAR [4-5]. To this aim, we have recently proposed a CMOS compatible OLWA that provides directive radiation at 1550 nm through the excitation of a LW guided mode into a dielectric waveguide comprising periodic silicon perturbations [6]. The presence of silicon facilitates beam control via electronic or optical excess carrier generation which in turn modifies its optical parameters (such as refractive index and absorption coefficient) [7-9]. Here, we study the input mismatch varying free space wavelength for two designs, and then focus on one structure and analyze beam scanning at broadside for varying free space wavelength and excess electron-hole carrier density in the Si perturbations via current injection (electronic control) or optical absorption (optical control).

II. Proposed Optical Leaky Wave Antenna

In [6] we have shown the agreement between 2D and 3D calculations for the signal wavemode traveling in the OLWA at the free space wavelength of 1550 nm. For simplicity, here we analyze the 2D model (invariant along z) reported in Fig. 1, with the material parameters in Table I. The waveguide is made of silicon nitride (Si_3N_4), is 100 µm long (along x), with w = 1 µm. The waveguide is sandwiched between two silica glass (SiO_2) domains 100 µm long (along x) and 9.5 µm wide (along y). The remaining space is assumed to be free space with unity refractive index. To provide directive radiation, the waveguide is perturbed with N silicon (Si) perturbations, positioned periodically (with period d) along the x direction on the bottom side of the Si_3N_4 waveguide (along y), and symmetrically with respect to the center of the waveguide (along x).

TABLE I. OLWA Material Parameters.

Waveguide (Si_3N_4)	Silica domain (SiO_2)	Si
$n_w = 1.67$	$n_h = 1.45$	$n_{Si} = 3.48$

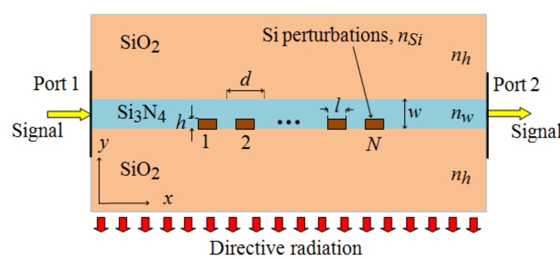

Figure 1. 2D model of the proposed OLWA made of an integrated Si_3N_4 waveguide and periodic Si perturbations.

III. Working Principle

A guided wave (signal) is injected from the left side (simulated port size is 2.4 µm) of the antenna at the free space wavelength λ_0 = 1550 nm, with electric field polarized along z. When this guided wave encounters the perturbed section of the waveguide, it transitions into a LW, slowly decaying while traveling. The periodic perturbations create a radiating $n = -1$ harmonic with wavenumber $k_{x,-1} = \beta_{-1} + i\alpha$, with $\beta_{-1} = \beta - 2\pi / d$ (β is the fundamental wavenumber in the perturbed waveguide, close in value to the one in the unperturbed waveguide). For comparison, we analyze the two sets of Si perturbations proposed in Table II. Both designs are aimed to radiate at broadside, i.e., along the $-\hat{\mathbf{y}}$ direction. Power is also radiated in the $+\hat{\mathbf{y}}$ direction, though radiation toward the bottom side of the waveguide is stronger. The LW

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radiation will determine the directive radiation pattern as in Fig. 2 in free space, previously confirmed against two theoretical methods and two full-wave simulators in [6].

TABLE II. DIMENSIONS OF THE TWO PERTURBATION SETS.

Perturbation set	Dimensions		
	l [nm]	*h [nm]*	*d [nm]*
1	485	300	970
2	500	500	1030

A very directive radiation is generated, with half-power beamwidth of about 1.4º for Set 1 and 1.5º for Set 2, with maximum radiation at $\phi_M \approx -93.4°$ and $\phi_M \approx -92.5°$, respectively (both have $\beta_{-1} << k_0$, $\alpha << k_0$). For Set 1, the radiation in the top half space is about 4 dB smaller than the one in the bottom half, whereas for Set 2 is about 8 dB smaller.

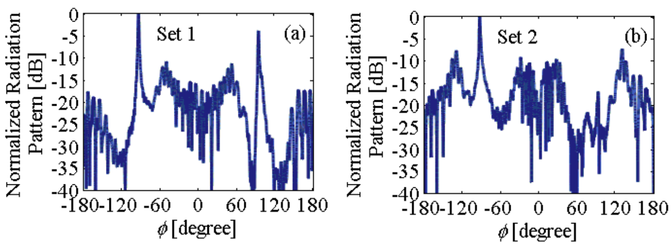

Figure 2. Directive radiation patterns at 1550 nm of OLWAs with (a) Set 1, and (b) Set 2.

IV. INPUT MISMATCH AND BEAM SCANNING VARYING WAVELENGTH AND SI OPTICAL PROPERTIES

The variation of the silicon refractive index versus wavelength is modeled by using the Sellmeier's equation [10] (note that this model was used also in [6] in Sec. 4.1 and Sec. 4.3 when varying the free space wavelength). The magnitude of the reflection coefficient $|S_{11}|$, and $1-|S_{11}|^2$ dependence versus free space wavelength are shown in Fig. 3 for both perturbation sets. Note that in both cases the $|S_{11}|$ peaks at a particular wavelength (λ_0 = 1517.5 nm for Set 1, λ_0 = 1515 nm for Set 2), which is close to a radiation with maximum at $\phi_M \approx -90°$ (i.e., $\beta_{-1} \approx 0$), shown for Set 1 in Fig. 4, red curve, as already observed in other leaky wave antennas at microwave frequencies [11]. As an example, we show in Fig. 4 the radiation pattern for Set 1 at selected free space wavelengths, normalized to the maximum of the radiation at λ_0 = 1550 nm. The maximum radiation angle has a clockwise shift for increasing wavelength. Note that the maximum level of the radiation drops about 5 dB for λ_0 = 1517.5 nm and about 7.5 dB for λ_0 = 1450 nm with respect to the level at λ_0 = 1550 nm. This is mainly related to the variation of the leaky wave attenuation constant α and input mismatch. At λ_0 = 1517.5 nm, assuming to have an excess electron-hole carrier density of 10^{19} cm^{-3} in each Si perturbation (refer to [6], Sec. 5, for the induced variation in the Si refractive index), the maximum of the radiation increases about 3 dB and rotates (clockwise) about 0.8° with respect to the case in Fig. 4, red curve. This result opens up to several interesting applications (e.g., switching). Beam control can be further enhanced by embedding the OLWA into a resonator.

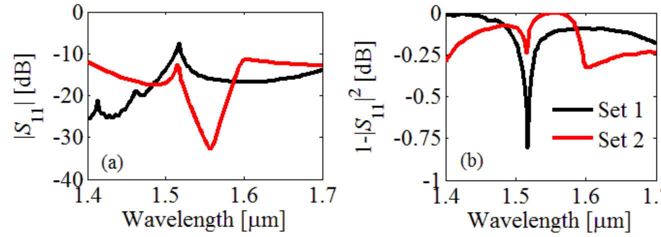

Figure 3. (a) $|S_{11}|$ and (b) $1-|S_{11}|^2$ versus free space wavelength for the perturbations in Table II.

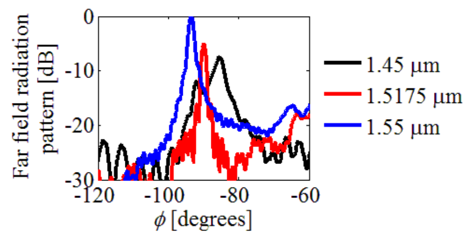

Figure 4. Beam scanning varying free space wavelength.

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