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# Narrow Beam Radiation from a CMOS Compatible Leaky Wave Optical Antenna

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Abstract: CMOS compatible leaky wave optical antennas are proposed and analyzed for electronically controlled radiation pattern generation. Very directive far field radiation pattern ( $>15\text{dB}$ ) is generated from a  $\text{Si}_3\text{N}_4$  leaky wave antenna with silicon periodic perturbations.

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OCIS code: (230.7390) Waveguides, planar; (050.6624) Subwavelength structures

## 1. Introduction

In this paper, we propose and analyze radiation patterns of CMOS compatible leaky wave optical antennas. In particular, we design  $\text{Si}_3\text{N}_4$  leaky wave optical antennas with silicon periodic perturbations in which the refractive index and the absorption coefficient can be electronically tuned to control far field radiation pattern. Preliminary results demonstrate that very directive radiation pattern with  $>15\text{dB}$  directivity is achievable.

Very directive near-IR optical antennas with electronically controlled beam steering and radiation pattern are subject of great interest for applications such as planar imaging and LIDAR. Instead of resorting to beam forming networks and phased array antennas consisting of near-IR optical arrays that require a large number of electronically controlled optical waveguides and relative phase shifters, CMOS compatible leaky wave antennas can provide desired radiation pattern and electronic control on the beam form. In particular, leaky wave optical antennas are attractive because they require a single feed point and electronically tunable periodic perturbations of the waveguide that leads to the controlled leaky radiation. The dielectric near-IR antenna consisting of silicon perturbations can be used to transform a guided mode into a leaky mode, thus radiating in a region of space. This radiation phenomenon can be precisely described by using the concept of leaky waves (LWs). Recently, LW parameterization has been used to explain enhanced directivity of a corrugated thin silver field with a subwavelength hole [1]. It has been shown that the periodicity produces a spatial harmonic of the plasmon wave in the visible region. LWs have also been used to parameterize radiation from a quasi-crystal waveguide [2]. In optoelectronics domain, Silicon-On-Insulator (SOI) devices have been characterized with the combination of optical properties and microelectronics characteristics of silicon devices based on an insulator layer, to reduce parasitic device capacitance and keep good mode confinement with low loss along the waveguide, and thereby improving performance on electronics and optical properties [3-6]. In this paper we present the preliminary results that combine the developments in silicon photonics and LWs to develop CMOS compatible optical antennas.

## 2. Results and discussion

Figure 1 illustrates the geometry of the leaky wave optical antenna and the near field radiation. The optical antenna is made of a  $\text{Si}_3\text{N}_4$  waveguide with height =  $1\mu\text{m}$  and refractive index of 1.67. The waveguide has  $4.5\mu\text{m}$   $\text{SiO}_2$  cladding on the top, and the substrate is made of  $\text{SiO}_2$ . The periodic perturbations at the bottom of the waveguide are made of silicon strips with dimensions  $300\text{nm} \times 485\text{nm}$ . The result shown below is performed based on 30 perturbations with a periodicity  $d = 970\text{nm}$ . The fundamental mode of light at  $1.55\mu\text{m}$  (free space wavelength), polarized along  $z$ , is chosen to propagate in the waveguide. The field pattern is calculated by the finite element method provided by COMSOL. Here we investigate the radiation pattern in the region below the waveguide. In particular, the far field radiation pattern is investigated to determine the directivity of the antenna and how it varies with respect to variations in silicon strips.

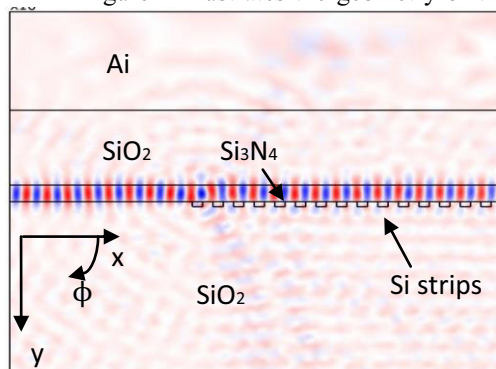


Figure 1. The periodic structure along  $\text{Si}_3\text{N}_4$  waveguide in the  $\text{SiO}_2$  substrate. The optimized period  $970\text{nm}$  and the depth  $300\text{nm}$  of the cell are found after parametric study.

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We also investigate the nature of radiation and its physical parameterization. We demonstrate that radiation is achieved by

exciting a leaky wave. Its wavenumber is  $k_x^{LW} = \beta + i\alpha$  is complex, where  $\beta$  and  $\alpha$  are the propagation and attenuation constants along the  $x$  direction (the direction of the waveguide). The periodicity is used to create a spatial harmonic with propagation constant  $\beta_{-1} = \beta - 2\pi/d$  which falls in the visible region. Radiation at broadside (direction orthogonal to the waveguide) is obtained when  $|\beta_{-1}| \ll k_0$ , where  $k_0$  is the free space wavenumber.

A simple field expression can be used to describe the far field radiation pattern. The normalized far field magnitude  $|E_z^{ff}|$  is obtained by integrating the “equivalent aperture” field over the grating area with size  $L = 30 d$ , leading to the simple expression

$$|E_z^{ff}| \approx \left( \frac{1 + e^{-2\alpha L} - 2e^{-\alpha L} \cos[(k_0 \cos \Phi - \beta_{-1})L]}{(k_0 \cos \Phi - \beta_{-1})^2 + \alpha^2} \right)^{\frac{1}{2}}.$$

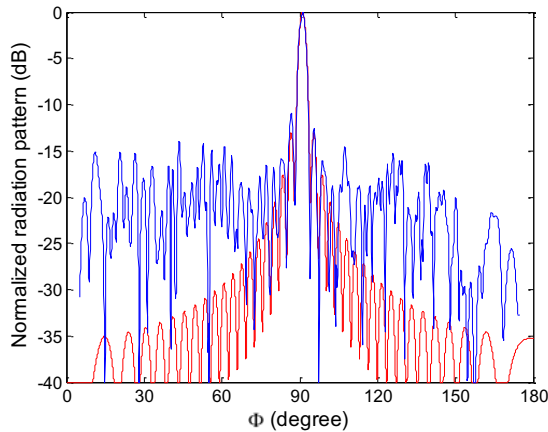


Figure 2. Comparison of the normalized far-field radiation patterns obtained by COMSOL (blue line) and LW theory (solid line).

In Fig. 2 we show that far field radiation pattern from the structure in figure 1 fed by a mode at the left end of the waveguide. A numerical analysis of the field data along the waveguide show that the normalized attenuation constant is  $\bar{\alpha} = \alpha/k_0 \approx 0.005$  whereas the normalized propagation constant is  $\bar{\beta}_{-1} = \beta_{-1}/k_0 \approx -0.0185$ . The far field radiation pattern obtained with the leaky wave theory is shown by the red line and it is in good agreement with the COMSOL results. The Leaky wave theory is important because it provides conditions for optimum radiation [2], and it provides closed form formula for beam direction and beam width.

During the presentation we will show how radiation characteristics can be controlled by controlling the perturbations, and how they can be predicted by the leaky wave theory.

### 3. Conclusion

In this work, the directive radiation performance of planar silicon strips periodic structure on the  $\text{Si}_3\text{N}_4$  waveguide has been investigated. The highly directive radiation has been obtained from the broadside with 20.09 dB directivity and a 3dB beam width of  $\Delta\phi_{3dB} \approx 2.6^\circ$ . The LW theory has paved the way to and parameterize the radiation of planar periodic structures and design desirable radiation patterns of optical radiators based on CMOS technology. The wave beaming of the optical radiator can be steered by combining the electronic and optical control from the intrinsic quality of the SOI device.

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