# Uniform and Non Uniform Optical Leaky-Wave Antennas for Field Shaping

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***Abstract*—The concept of optical leaky wave antennas based on periodic perturbations in a dielectric waveguide has been demonstrated to provide directive radiation in far field. Moreover the radiated field from such silicon-on-insulator and CMOS compatible antenna systems can be modulated through controlling the excess carrier density in silicon inclusions, and the radiation modulation with high extinction ratios were achieved by integrating the antennas in resonator topologies. In this paper we extend this concept to optical waveguides with non uniformly distributed perturbations as a method of shaping the antenna near field. The scattering of electromagnetic waves through such perturbed waveguides can be engineered using array theory or a leaky wave model. The resonator integration and Si-based designs combined with the near-field shaping technique proposed here can lead to applications such as tunable near field detection. In this paper we present a theoretical framework as a proof of the proposed concept with a CMOS compatible optical antenna.**

## I. INTRODUCTION

The concept of highly directive optical leaky wave antennas (OLWAs) has been introduced in [1]-[4]. CMOS-compatible design configurations allow OLWAs to be viable optical antennas open to integration with electronics. In [1],[2], we presented an OLWA with uniformly spaced perturbations buried inside a dielectric optical waveguide that lead to directive radiation that can be electronically modulated when excess carrier densities inside silicon inclusions are controlled.

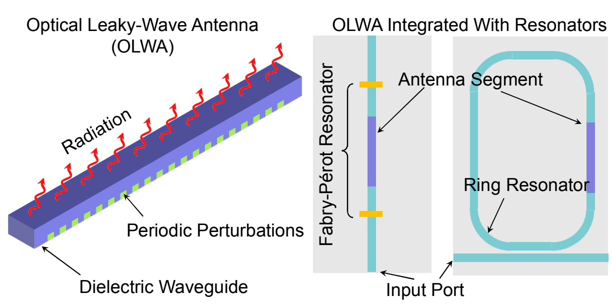


Fig. 1. [Left panel] Illustration of Silicon based OLWA topology, [right panel] OLWA integrated with Fabry-Pérot resonator and ring resonator topologies.

The radiation from OLWA arises from a leaky wave spatial harmonic obtained by introducing periodicity to the system. The perturbations, with period $d$, lead to the excitation of spatial harmonics (i.e. Floquet harmonics) with spectral separation equal to $2\pi / d$. The harmonics propagate with wavenumbers $k_n = k_{\mathrm{mode},0} + 2\pi n / d$ with $n = 0, \pm 1, \pm 2, \ldots$ where $k_{\mathrm{mode},0}$ is the fundamental Bloch wavenumber. In general the $-1$ harmonic is tuned as a fast wave and it radiates in a narrow angular region provided that the perturbations are small. The inclusion of silicon as either perturbations or waveguide material in the OLWA design allows for tuning the silicon refractive index via excess carrier density [2], thus the guided wave's propagation constant can be modulated. In general this modulation is limited but its impact is boosted with the integration of the OLWA into resonators with high-quality factor such as the Fabry-Pérot resonator [2],[3] and the ring resonator topologies [4] as in Fig. 1. The resonance control yields large variations in the radiated field from the OLWA segment. Here we extend the OLWA concept by resorting to non uniformly spaced perturbations on an optical waveguide. The idea consists in forming a phase front of a converging field at a focus by properly spacing the perturbations. In the following we present the theoretical model first and show some analytical results. We note that the presented topology can be also integrated into resonators, and that inclusion of Si can lead to tunability of the proposed scheme.

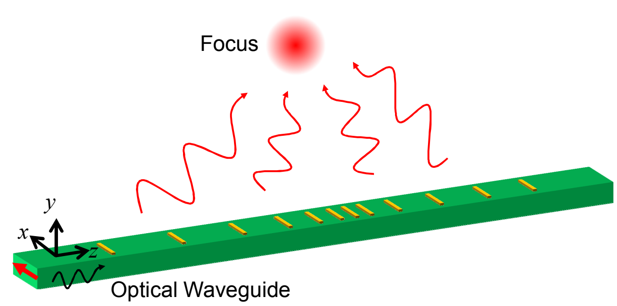


Fig. 2. Illustration of the optical waveguide with scatterers deposited on top of the waveguide. The distributed emission is engineered to create focus.

## II. OLWA FOR NEAR FIELD FOCUSING

The antenna near field shaping is realized with a series of scatterers deposited on an optical dielectric waveguide as illustrated in Fig. 2. These scatterers perturb the propagating mode inside the dielectric waveguide and lead to radiation. The scatterer positions are tuned such that the mode in the waveguide leaks into the surrounding medium and, as an representative case here, converge in a focal point.

The perturbations in this case are, locally, almost periodic and the period is adiabatically modified along the waveguide length such that the leaky wave's propagation constant and radiation direction is controlled locally.The overall radiation from the system focuses at a certain desired location. From the array theory perspective, the focusing of the radiation from such a system can be straightforwardly engineered. Assume that the scatterers are small enough to be modeled as dipolar scatterers and do not couple with each other significantly. The excitation phase of each scatterer is determined by the phase of the guided field at the scatterer position.The required phase profile of dipoles in order to have focusing is known as a function of their position. Using a holographic process, the scatterers should be located at positions where the guided wave's phase is equal to the value of the phase profile of a wave converging to the focal point. For a waveguide along the $z$ axis, the scatterer positions are found by the solutions of $\measuredangle \exp\left(ik_{\mathrm{mode}}z\right) = \measuredangle e\left(-ik_0\left|\mathbf{r}_f - z\hat{\mathbf{z}}\right|\right)$ where $\mathbf{r}_f$ is the focus position and $k_0$ is the wavenumber in the surrounding vacuum. In the following we consider an example where the modal wavenumber is $k_{\mathrm{mode}} = 1.5k_0\left(1+0.02i\right)$, taking into account the small attenuation as the mode propagates along the $+z$ direction. The guided mode is assumed to be polarized along the $x$ direction, thus aligned with the scatterers' polarizability axis. The scatterers are designed to be positioned between $z = -5\lambda_0$ and $z = 5\lambda_0$, the focus is located at $\left(x,y,z\right) = \left(0,10\lambda_0,0\right)$. The scatterer positions are calculated with the given formula, and also by limiting the closest distance between neighboring scatterers to $0.25\lambda_0$. In Fig. 3, the phase of the guided wave (solid blue), the required phase for converging phase front (dashed red) and the solution's to scatterer positions (green circles) are shown.

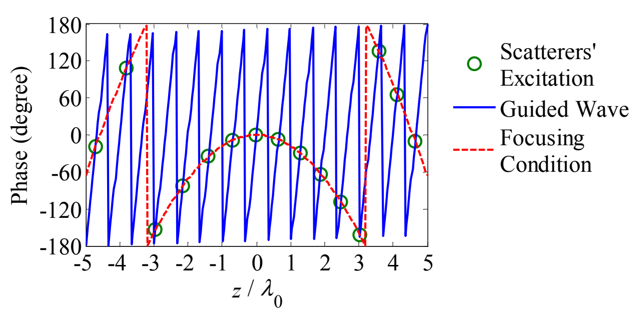


Fig. 3. The phase of the guided wave (solid blue), the required phase for converging phase front (dashed red) and the phase of the scatterers at the solution points (green circles).

The scattered field is obtained by summing radiation contributions from the dipolar elements polarized along the $x$ direction, with the excitation phase and amplitude given by $e^{ik_{\mathrm{mode}}z_s}$, where $z_s$ are the scatterer positions shown in Fig. 3. In Fig. 4, we plot the magnitude of the electric field vector on the $yz$ plane (left panel) and focal ($xz$) plane at $y = 10\lambda_0$ (right panel) in dB. The field focusing property is clearly visible at around $y = 10\lambda_0$, however the spot on the $xz$ plane at $y = 10\lambda_0$ is not narrow in the $x$ direction because of the dipole pattern.

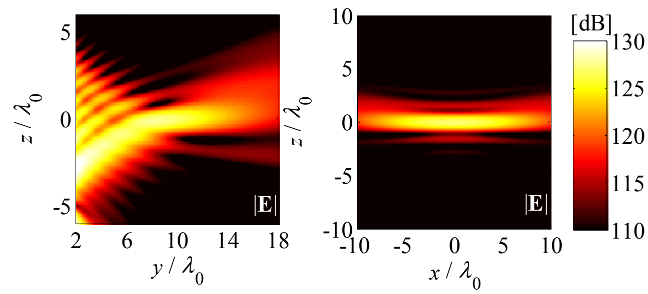


Fig. 4. [Left panel ] Electric field magnitude on $yz$ plane, converging around $y = 10\lambda_0$. [Right panel ] Electric field magnitude on $xz$ plane at $y = 10\lambda_0$, showing focusing in the x direction

In order to tighten the focal spot size on $xz$ plane along the $x$ direction, several optical waveguides along $z$ are laid out in array configuration. The results for a case with 6 optical waveguides separated by $2\lambda_0$ along $x$, are reported in Fig. 5, where a very tight focus is clearly visible in the $xy$ plane.

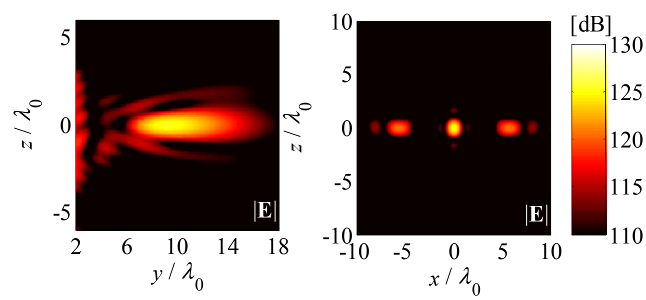


Fig. 5. As in Fig 4, for 6 parallel optical waveguides spaced evenly between $x = -5\lambda_0$ and $x = 5\lambda_0$.

In conclusion, we present a CMOS based near field focusing topology fed through an optical waveguide based on the OLWA concept. The tunability can be achieved by using Si-based designs integrated with a resonator as in Fig. 1.

## Acknowledgement

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