Integrated optical leaky wave antenna for 1D optical phased arrays in LiDAR

L. Van Iseghem,[1,2] and W. Bogaerts[1,2]

[1] Ghent University - IMEC, Photonics Research Group, Department of Information Technology, Ghent Belgium

[2] Center for Nano- and Biophotonics (NB-Photonics), Ghent, Belgium

We show a novel optical antenna concept based on a leaking guided mode. We performed extensive numerical modelling and we present the design process based on these results. Results indicate that this antenna concept could solve significant scalability issues with apodized diffraction gratings for engineering antennas with optimized beam profiles.

Introduction

Integrated silicon photonics is a fast growing technology enabling many different applications because of the scalability of integrated systems. Light detection and ranging (LiDAR) applications can also benefit from such a scaling, where densely integrated beam steering solutions can increase the performance and decrease the cost of such systems. An integrated beam steering can be realized with mechanical systems such as MEMS to physically rotate the beam. Another approach for beam steering which is more suited for dense integration is feeding light into an optical splitter circuit with phase shifters and feeding these coherent signals with a certain phase relation to an optical antenna array (OPA). (see Fig. 1b) [1]

Integrated 1D optical phased arrays

The steering resolution of an OPA is determined mainly by the number of antennas and the aperture size is determined by the antenna spacing. On top of that the spacing between antenna's needs to be controlled precisely to maintain the correct phase relationship between signals (although this can be mitigated by adjusting phase shifts in the splitter circuit). For these reasons, it is beneficial to space a large number of optical antennas in such a system close together. This increases resolution and aperture size while minimizing footprint and fabrication variation.

The dense integration in silicon photonics is possible due to the high index contrast on this platform, allowing for narrow waveguides and small bend radii. This enables a dense spacing (small period P_x) of long optical antennas as illustrated in fig. 1b. The 1D OPA with long emitters is more attractive for dense integration as compared to a matrix of discrete 2D grating couplers because the routing of signals increases the spacing between the antennas. In other words, a 1D OPA is much more scalable than a 2D OPA [1].

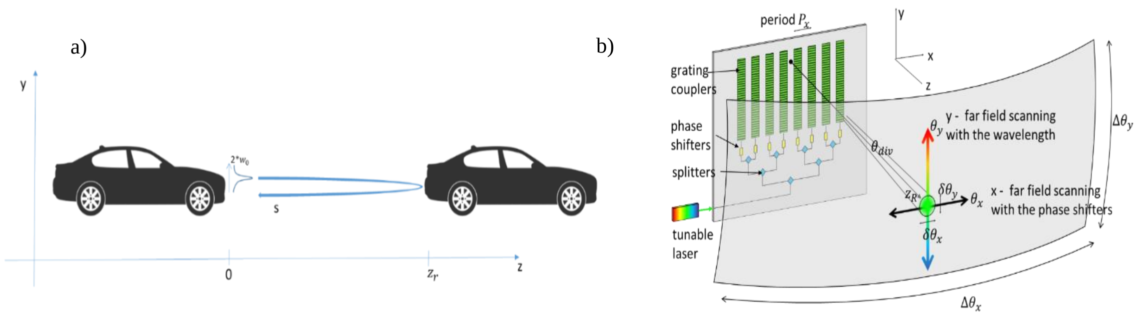

Figure 1a) LiDAR in forward looking automotive b) Beam steering with a 1-dimensional optical phased array (from [1])

In forward-looking automotive LiDAR, as shown in Fig. 1a, one wants to detect an object at a distance of at least 200m. This means the Rayleigh range of the beam $z_r > 200m$, which requires an optical antenna with an emitting surface of 30×30mm^2. [1] While the high index contrast is helpful for increasing the density and overall performance, it also increases the sensitivity to small geometric variations. This high sensitivity to the geometry makes it difficult to create a weak grating (i.e. long antenna) in silicon waveguides, because perturbations in geometry will scatter the guided modes to strongly resulting in a beam waist too small for the desired Rayleigh range (a grating can be interpreted as a phased array of scattering elements).

To actually emit a Gaussian beam the grating strength needs to have a certain spatial profile, where the radiated power from the guided mode varies with propagation distance. A well-known technique to achieve this is to apodize the grating, increasing the amplitude of index perturbation at each period to increase grating strength gradually. While this is a good approach in theory, earlier mentioned problems with sensitivity demand an unfeasible control on fabrication of these long gratings (which is challenging because of their large length).

Lateral leakage in rib waveguides

To help mitigate these scaling challenges of both bringing a large number of antennas as close as possible while tuning the radiation per propagation length from very weak to very strong we propose a novel approach to create long integrated antenna structures, based on a phenomenon exhibited by guided TM modes in rib waveguides called lateral leakage. The TM mode actually behaves as a bounded mode in a radiation continuum for certain geometries, meaning that for certain geometrical configurations the guided mode is isolated from a radiation continuum. This means a bound mode (no radiation) can be changed into a radiating mode by altering certain parameters such as waveguide width or rib height. [2]

The guided TM mode has a lower phase constant than TE modes in the slab, allowing phase matching between the guided TM mode and TE slab modes at a certain angle θ. As this coupling between TM and TE modes happens at each side wall, the waveguide's edges can be seen as 2 interfering emitters spaced apart with the core width of the waveguide. At certain widths the TE slab modes are out of phase, canceling each other out. This means there are singular width values ("magic widths") for which the TM mode becomes bound in continuum (guided), as can be seen in Fig. 2. [2]

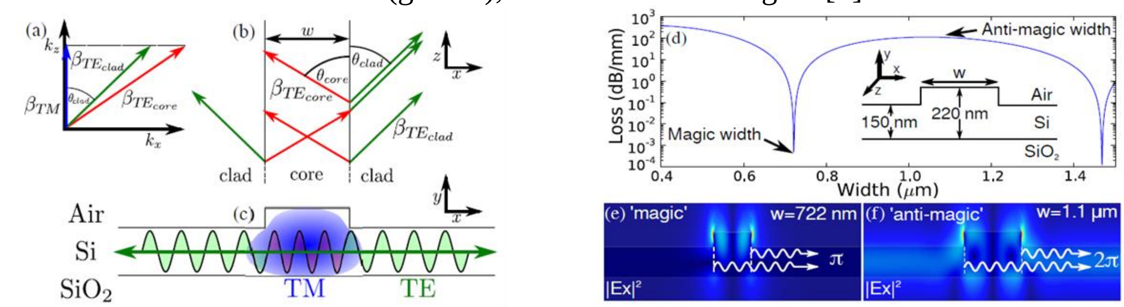

Figure 2 Lateral leakage in rib waveguides (taken from [2])

Optical leaky wave antennas inspired on lateral leakage

While the power is transferred laterally from the propagation direction in a lateral leakage scheme (hence the name), the principle can actually be rotated 90 degrees directing power in the vertical direction. In this case a TE mode can become bound in a continuum under certain geometrical configurations. While in lateral leakage the bound conditions are found for certain “magic widths”, here the coupling to the slab is determined by another underlying physical mechanism.

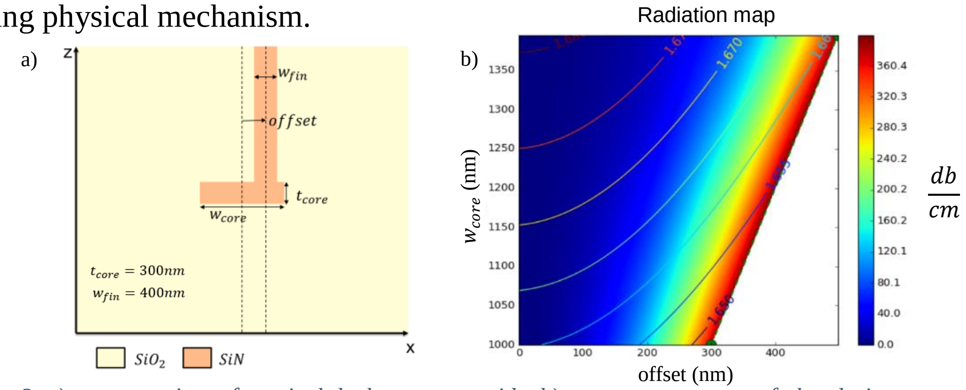

Figure 3 a) cross-section of vertical leakage waveguide b) parameter sweep of the device, $t_{core} = 300nm, w_{fin} = 400nm$

The guided TE mode is coupled the vertical slab TM mode (from here on referred to as the “fin”) as soon as the in-plane symmetry is broken. The configuration in Fig. 3a shows a symmetrical geometry where the TE mode of the waveguide core is guided (bound in the continuum, no radiation). When the offset is increased, this symmetry is broken more and more and the coupling between the guided TE mode and the TM mode in the fin at a certain angle increases. We swept the offset in the cross-section in Fig. 3a, simulating it using a film mode matching mode solver with transparent boundary condition on the top. As follows from Kramers-Kroning conditions, the real part of the effective decreases for an increasing imaginary part. This means that when the loss (radiation) of the geometry increases, the phase constant (effective index) decreases. In an optical phased array, the phase relationships between antennas are important, and it is required that the phase velocity of each antenna remains constant. To achieve a constant effective index (real part) together with an increasing radiation (loss), the waveguide core width w_{core} can be varied together with the offset. This results in a mechanism to tune the radiation strength of the antenna while keeping a constant phase velocity. Solutions that fulfill this constraint are found by mapping the real part of index contours on the radiation map of the geometry. For an index contour path, the phase velocity remains constant while the radiation can be configured from very weak to very strong.

Proposed design methodology for leaky wave antennas

If one index value is chosen (i.e. $n_{eff} = 1.665$), we have a function that maps the offset (geometrical parameter) to a certain corresponding width for the given phase constant (real part of effective index). Each offset also corresponds to a radiation value in dB/cm.

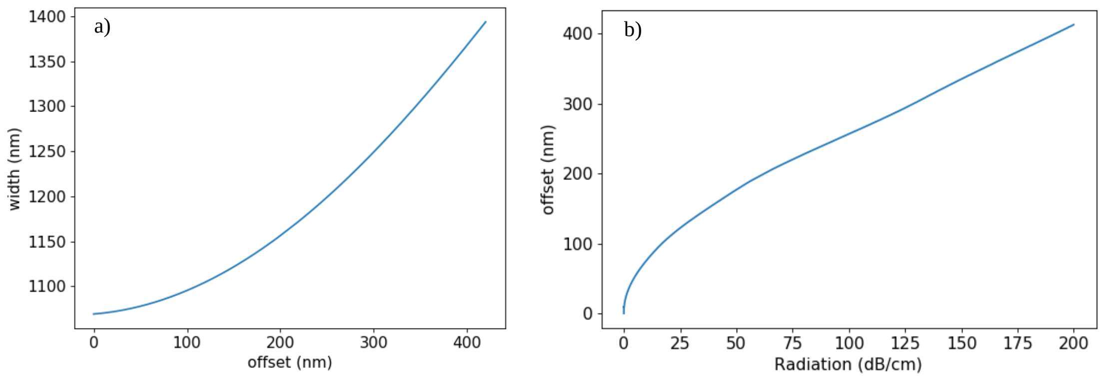

Figure 4 a) offset - width curve b) radiation - offset curve

Now the geometry to obtain a certain spatial radiation profile can be determined from these functions. If we start with a desired output Gaussian power profile curve as given in fig. 5a, the required radiation strength at each position y can be determined (fig. 5b), from which both the theoretical required offset and core width at that position can be found (fig. 5c).

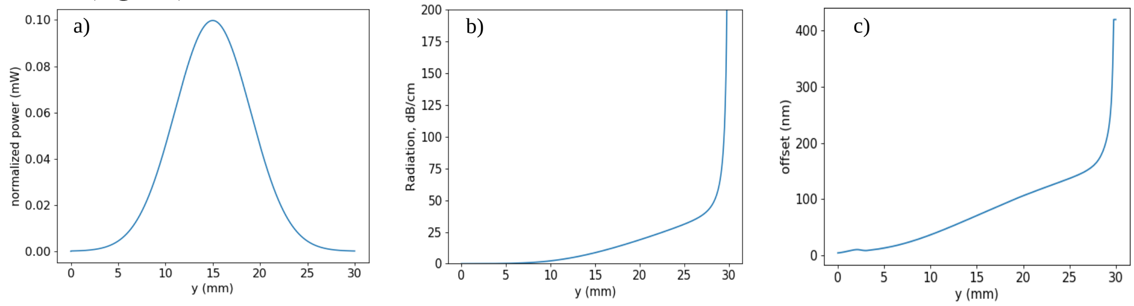

Figure 5 a) desired output profile b) corresponding radiation strength required c) antenna design, offset value at each position y

From this, offset and width values at each distance y can be determined resulting in a tapered antenna design shown below:

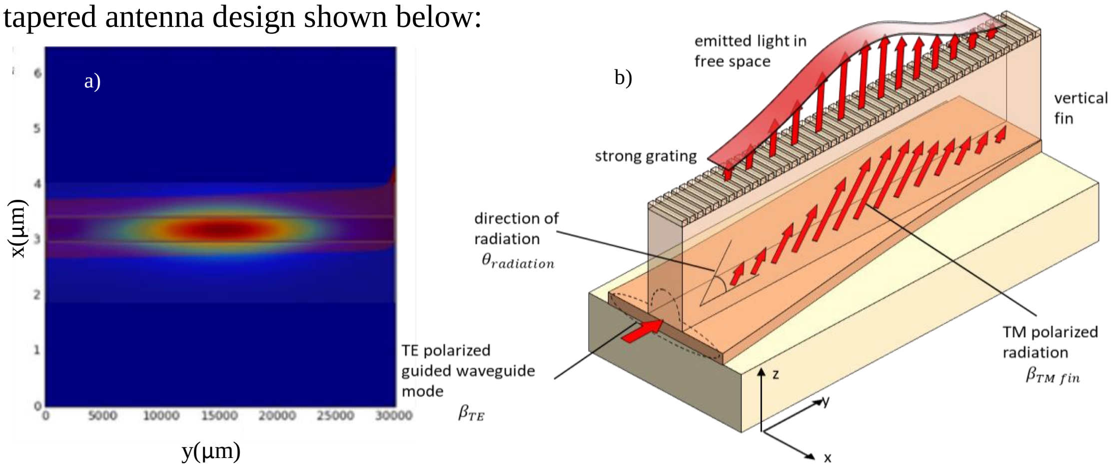

Figure 6 a) simulation of antenna design b) conceptual 3D drawing of antenna design concept

The simulations in fig. 6a were carried out to simulate the coupling from the TE guided mode to the TM polarized radiation in the fin. After this the emitted light still needs to be coupled outside the chip surface. This can be done with a strong uniform grating on top of the fin, without apodization, as shown in fig. 6b. This way unfeasible fabrication requirements are avoided, as the sensitivity from the loss to the offset is weak.

Conclusion

We present a new optical leaky wave antenna concept (conceptually similar to mm-wave leaky wave antennas) to mitigate scalability issues associated with other approaches such as apodization of a long grating. This approach is fundamentally more robust against fabrication variations and can be designed to generate any wanted power profile on the output.

References

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