

Compact Nano-Antenna Emitters for Optical Phased Array Applications.

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Abstract: We propose and experimentally demonstrate nano-antenna emitters coupled to a dielectric waveguide. Initial measured emitter efficiencies are 4.9 – 13% with simulations predicting > 50% efficiencies with bandwidths exceeding 300nm in more advanced and ideally fabricated geometries.

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1. Introduction

Optical phased arrays (OPA) have recently attracted attention as compact, electromagnetic interference-free alternatives to their RF counterparts [1]. One of the building blocks of such phased arrays are high efficiency compact vertical emitters. Using CMOS-compatible silicon-on-insulator technology for fabricating such emitters provides for compact integration using a well established platform. While vertical nanoemitters have been widely proposed in literature [2, 3], most of them rely on grating couplers, which provide for a bulky structure, making it difficult to closely integrate the large number required to implement wide angle steering in an optical phased array. In this paper we demonstrate compact vertical nanoemitters in the C-band, with overall length of 1 to 4 λ . Emitters are based on a silicon nitride (Si_3N_4) waveguide coupled to an aperture metal nanoantenna above it, with the addition of a metal ground plane located a distance of $3\lambda/4$ underneath the antenna plane. By laterally repeating the aperture in the metal antenna plane, the coupling coefficient μ between the antenna and the waveguide can be increased approximately by a factor of \sqrt{M} , where M is the number of times the aperture is repeated. Experimental efficiencies of the initial fabrication run of such nanoemitters are measured to be 4.9-13%.

2. Theory/Simulation Results

Nanoemitters demonstrated in this paper have been proposed by Yaacobi et al [4]. Treating metal nanoantenna as a resonator perturbed by an electric field from dielectric waveguide [5], coupling coefficient μ between the nanoantenna and the waveguide can be written as $\mu = \frac{-j}{4} \omega \int \Delta \epsilon \tilde{\mathbf{E}}_r^* \cdot \tilde{\mathbf{E}}_{wg} dv$, where $\Delta \epsilon$ is the difference in the electric permittivities between the antenna metal and the surrounding dielectric, $\tilde{\mathbf{E}}_{wg}$ is the three-dimensional electric field mode in the waveguide, and $\tilde{\mathbf{E}}_r$ is the radiated electric field. Since metals have large permittivities, the coupling coefficient between metal and dielectric is larger than dielectric-dielectric one, allowing for greater emission efficiency in such nanoantennas. In addition, repeating the nanoantenna structure laterally will increase the integral volume in the coupling coefficient formula above, increasing μ by the factor of \sqrt{M} , where M is the number of times the antenna structure is repeated. Figure 1 (a) shows the proposed nanoantenna structure. A Si_3N_4 waveguide, with dimensions of 700x220 nm is imbedded into SiO_2 and coupled to an aluminum aperture nanoantenna using a surface plasmon mode. An additional metal ground plane located $3\lambda/4$ underneath the antenna plane minimizes the emission losses due to down-reflection. Figure 1 (b) shows a 3D finite-difference time domain (FDTD) simulation of a 3x3 apertures nanoantenna with dimensions specified above. Simulated efficiencies of proposed nanoantennas are 12%, 33%, and 52% for 1x1, 1x3, and 3x6 aperture nanoemitters respectively. Importantly, these nanoantennas exhibit bandwidths that exceed 300nm, substantially larger than has been demonstrated with grating-based couplers. The large bandwidths are due to the strong coupling provided by the metallic structure and the resulting short length of the emitter.

3. Results and Discussion

Proposed nanoemitters have been fabricated at Sandia National Labs, using e-beam lithography. Figure 2 (a) shows the image of a 3x3 aperture structure taken with scanning electron microscope. As a result of fabrication constraints, the

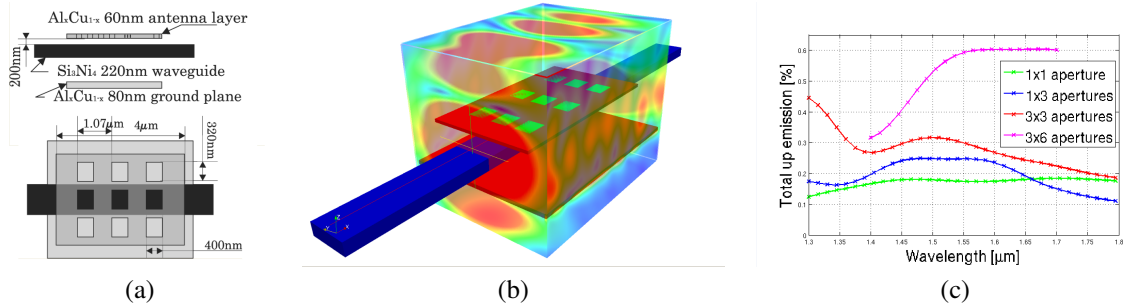


Fig. 1. (a) Nanoemitter structure; (b) 3D FDTD simulation of a 3x3 emitter; (c) Simulated up emission

initial fabricated structures exhibit some significant differences in nanoantenna dimensions, such as different antenna-waveguide separation, and different antenna plane dimensions than the design. All proposed devices have been re-simulated to account for those fabrication changes; the final efficiencies of as-fabricated devices are shown in Figure 2 (c). A high sensitivity infrared camera was used to image all of the devices, and a 0.68NA lens was used to collect the light emitted upwards. Figure 2 (b) shows measured emitter efficiency vs wavelength. The curves resemble simulated data from 1 (c), however measured efficiencies appear smaller by a significant factor. We account for this factor by examining the emission angle for our nanoemitters. Fabrication deviations described above resulted in each device having several radiation lobes, centered at $\pm 30^\circ$ angles from the vertical emission. Capturing such emission requires a significantly higher numerical aperture (NA) lens than the 0.68 used for these measurements. Simulated results suggest that the fraction of the light captured by the lens is 20%, 14%, and 60% for 1x1, 1x3 and 3x3 structures respectively. Figure 2 (c) shows a simulated efficiency of the 3x3 emitter, adjusted for the energy not captured by the lens, overlaid with measured results. We attribute the remaining difference between the simulated and measured curves to the coupling loss from the fiber coupling into the waveguide. This loss was measured for 1550 nm and was assumed to be the same for 1520-1620nm. Overall measured efficiencies at 1550 nm for vertical nanoemitters presented in this paper are 4.93%, 7.11% and 13.04% for 1x1, 1x3 and 3x3 apertures emitter structures respectively. While the initial measured efficiencies are not yet as high as grating-based emitters, the potential for extremely compact and wide-band operation offered by nano-antenna-based emitters is compelling. Additional and updated measurement results will be presented.

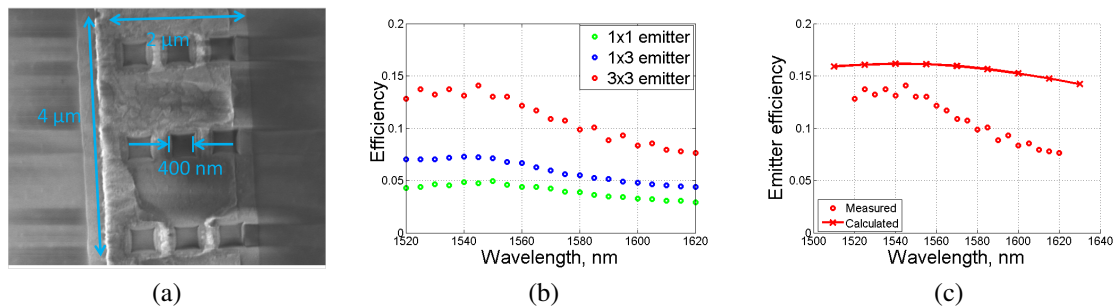


Fig. 2. (a) SEM image of a 3x3 emitter; (b) Experimental efficiencies; (c) Experimental vs calculated efficiency for 3x3 apertures emitter

References

1. K. V. Acoleyen, H. Rogier, R. Baets, Vol. **18**, No. 13, pp. 655-660, (2010).
2. M. Fan, M. Popovic, F. X. Kaertner, *Proceedings of Conference on Lasers and Electro-Optics*, (Optical Society of America, 2007), paper CTuDD3.
3. G. Roelkens, D. V. Thourhout, Roel Baets, *Optics Letters*, Vol. **32**, pp. 1495-1497 (2007)
4. A. Yaacobi, E. Timurdogan, M. R. Watts, *Photonics Letters*, submitted Nov. 2011
5. H. A. Haus, *Waves and Fields in Optoelectronics*, pp. 197-207, (Prentice-Hall, 1984).