Efficient Coupling of Optical-Antenna Based nanoLED to a Photonic Waveguide

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Abstract: An optical-antenna nanoLED is coupled into an InP waveguide. Optical emission measurements of Yagi-Uda antennas show a 5x increase in forward coupled light, giving 70% waveguide coupling efficiency and directional emission.

1. Introduction

Nano-optoelectronic devices such as nano-emitters[1,2] and nano-photodetectors[3,4] show great promise for use in future ultra-low power optical interconnects. Such systems have the possibility of displacing traditional metal interconnects on integrated circuits to significantly reduce on-chip power consumption[5]. The nanoLEDs that use optical antennas to increase their modulation bandwidth[1] are particularly interesting due to their ultra-small size and their capability of high modulation bandwidth and high quantum efficiency. Any integrated photonic link, however, would require components to be coupled to a waveguide for transmission around a chip. Although waveguide coupled nanolasers have been demonstrated[6], there has yet to be a demonstration of a waveguide coupled nanoLED.

Here we demonstrate a nanoLED coupled to a multi-mode InP waveguide. Optical emission measurements of single optical-antenna nanoLEDs show coupling efficiencies of 45%. By utilizing a simple Yagi-Uda[7,8] antenna structure, waveguide coupling efficiencies of 70% are achieved with a front-to-back emission ratio of 1.6. Simulations are performed that confirm measurements, giving 50% coupling efficiency for single element antennas and 66% for Yagi-Uda antennas.

2. Structure

The nanoLED structure in this paper is based on the arch-antenna discussed previously with spontaneous emission enhancement >32x[1] and shown in Fig. 2(g). It consists of a nano-ridge of InGaAsP (150nm long, 35nm tall, and 29nm wide) that is uniformly covered in 3nm of TiO_2 with a gold bar deposited perpendicularly over it. In this study, the antenna rests on top of a 320nm thick InP layer that is patterned into a multi-mode waveguide 3um wide and 50um long by wet etching along crystal planes. By utilizing a Yagi-uda structure, increased coupling into the forward waveguide direction is achieved. The antenna elements are 50nm wide, 45nm thick, and the arch antenna is 250nm long. The entire antenna is bonded to a quartz carrier wafer by UV-cured epoxy.

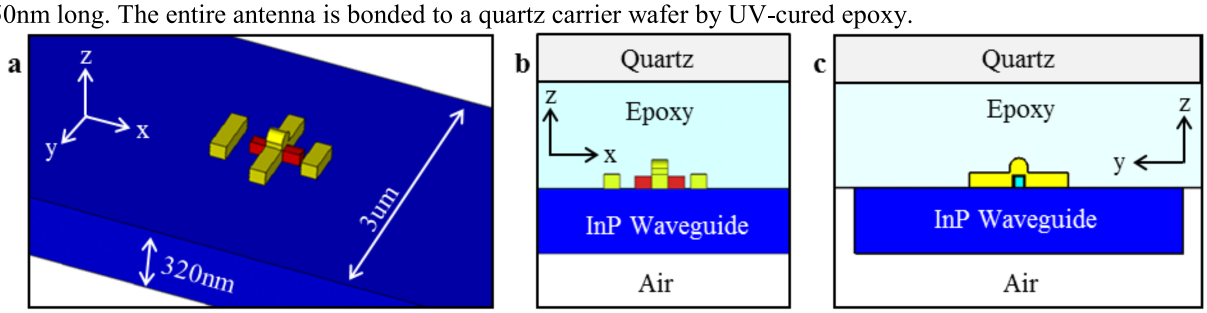

Figure 1. (a) Perspective and (b) side view of Yagi-Uda antenna on top of InP waveguide. (c) Front view of antenna structure with cut-plane through the center of the arch-antenna. Figures are not to scale.

3. Results

The InGaAsP ridge and the surrounding InP waveguide are optically pumped by a Ti:Sapphire laser with a center wavelength of 800nm. Optical emission from the subsequent ratiative recombination of carriers was then collected with a 100x objective with 0.8NA from both the top (epoxy-side) and bottom (air-side). Fig. 2(f) shows the spatially resolved optical emission radiated into air from a single element antenna coupled to the waveguide. Equal amounts of light are emitted out the two ends of the waveguide (~22.5% each), while ~55% of the light is uncoupled and comes straight from the nanoLED. A similar fraction of light is coupled to the waveguide for an un-enhanced bare ridge of InGaAsP (Fig.2.b.), though the intensity is ~10x lower. Fig. 2(e) shows the energy density profile of the antenna on waveguide structure depicted in Fig. 2(d). Finite element method simulations of this structure give a 50% coupling efficiency into the waveguide with light emission equally split between the forward and backward waveguide directions.

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Ideally, a light emitter would be able to transmit in a given direction down an optical waveguide. By adding passive reflector and director elements to the arch-antenna structure, a Yagi-Uda antenna is created which is well known for having directional emission. Optical emission measurements of this structure (Fig. 2(j)) show 5x higher intensity in forward coupled light than a single element antenna, giving a 70% coupling efficiency into the waveguide. In addition, light coming out from the forward-direction side of the waveguide is stronger in intensity than from the backwards-direction end by 1.6, demonstrating that the Yagi-Uda is preferentially radiating in the forward-direction.

Yagi-Uda antennas characteristically have a reflector element longer than the driven element and a director element shorter than the driven element. In the case shown, the arch-antenna is the driven element of the array. Due to the added impedance from the arch-matching network, the length of this antenna (250nm) is actually much longer than either the reflector or director. Maximum coupling was achieved when the length and spacing of the reflector (director) from the center of the arch antenna were 166nm (115nm) and 150nm (122nm) respectively.

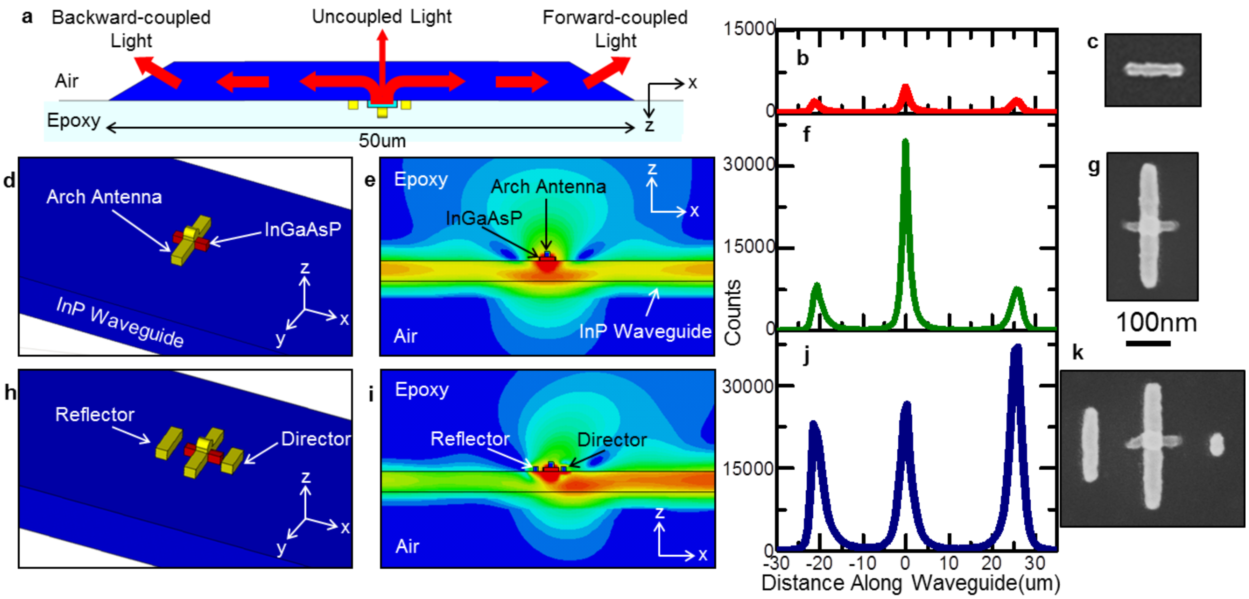

Figure 2. (a) Side view of Yagi-Uda antenna coupled to InP waveguide. The structure is flip-chip bonded to glass with epoxy, leaving the antenna fully embedded in epoxy. (b) Spatially resolved optical emission intensity from a bare ridge of InGaAsP coupled to an InP waveguide. (c) SEM image of bare InGaAsP ridge. (d) Schematic view (e) side view of energy density profile (f) spatially resolved optical emission intensity and (g) SEM of an arch dipole antenna on an InP waveguide. (h) Schematic view (i) side view of energy density profile (j) spatially resolved optical emission intensity and (k) SEM of a Yagi-Uda antenna on an InP waveguide.

In conclusion, we have demonstrated a waveguide-coupled nanoLED with enhanced spontaneous emission. By adding passive reflector and director elements 70% waveguide coupling is achieved with directional emission down the waveguide. Such waveguide coupled nanoLEDs with enhanced modulation bandwidth show promise for future ultra-low power on-chip optical networks.

4. Acknowledgements

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5. References

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