Design and Fabrication of Tapered Waveguides in AlGaAs for Coupling Light in Nanoscale Optoelectronic Devices

Nathaniel Burt, Electrical Engineering, Kansas State University

NNIN REU Site: Stanford Nanofabrication Facility, Stanford University
Principal Investigator: James S. Harris, Electrical Engineering, Stanford University
Mentor: Luigi Scaccabarozzi, Applied Physics, Stanford University
Contact: nburt@ksu.edu, harris@snowmass.stanford.edu

Abstract:

While typical frequency-conversion devices in use today require that optical signals be transformed by slow and power-consuming electrical circuitry, all-optical devices would be an appealing alternative, eliminating the need for electric conversion. Our work is concerned with improving the coupling efficiency in existing submicron-scale AlGaAs waveguides having an embedded microcavity. This can be achieved by adding a tapered structure at each end, which greatly increases coupling at both the input and the output facets. We have optimized parameters of two taper geometries through simulations. Measurements of relevant optical characteristics are presented.

Introduction:

The aim of this project is to design and fabricate a structure capable of coupling more light into an existing nanoscale all-optical frequency conversion device [1]. Because the device has sub-wavelength cross-sectional dimensions, a significant size mismatch exists between its tightly confined propagating mode and the field propagating in free space. The coupling efficiency is determined by the overlap integral between the fields on either side of the interface, so the mode size must be transformed toward the ends of the device to closely match the free-space field. A well-documented, highly effective solution involves adding a tapered section to each end of an optical device.

Preliminary Investigations:

Researchers have achieved modal expansion within optical devices using many types of waveguide tapers [2]. Two general types exist—tightly confining waveguides flaring outward at the ends and loosely confining waveguides with inward tapers at the ends. We have investigated the two laterally tapered structures shown in Figure 1.

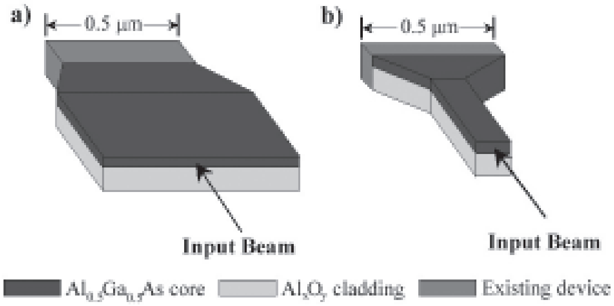

Figure 1: Laterally tapered waveguides.
a) conventional taper and b) inverse taper.

We simulated and optimized both end facet geometries using a semi-vectorial finite difference frequency domain scheme [3]. All structures were assumed to have a 200 nm thick $Al_{0.5}Ga_{0.5}As$ (n=3.3) core above a completely oxidized, 2.5 µm thick $Al_{0.97}Ga_{0.03}As$ (n=1.61) lower cladding, as these are inflexible parameters of the existing microcavity waveguide. The incident energy was approximated as a Gaussian beam having a $1/e^2$ radius of 2 µm.

The first structure of interest, a conventionally tapered waveguide, is similar to the existing device in that its upper cladding is air. It is attractive because it would require few changes in the fabrication process. The high index of refraction contrast between the core and air cover (3.3 to 1) causes the propagating mode to be tightly confined within the core. The structure flares laterally outward at both end facets, allowing horizontal expansion of the mode toward the ends of the device. Our simulations indicated that this conventionally tapered waveguide would yield a modest coupling efficiency of 32% at an optimum width of 4 µm.

While flaring the waveguide outward allows the mode to expand laterally, the mode must also expand in the vertical direction in order to closely match the Gaussian intensity distribution of the incident light. A waveguide having a very small core area at the end facets effectively squeezes the mode out of the waveguide, allowing for significant horizontal and vertical expansion of the mode. Our simulations indicated that a waveguide inversely tapered to approximately 170 nm in width would yield a coupling efficiency of just over 90%. It is logical that the most efficient end facet has a nearly square core given that the desired mode profile is circularly symmetric.

Device Fabrication:

The fabrication process begins with growth of a heterostructure by molecular beam epitaxy. A 2.5 µm thick $Al_{0.97}Ga_{0.03}As$ layer to be used as the lower waveguide cladding is deposited onto a GaAs substrate, followed by a 200 nm thick $Al_{0.5}Ga_{0.5}As$ layer that later forms the waveguide core. Next, the positive electron-beam photoresist PMMA (950K, 2%) is spun onto the wafer to a thickness of approximately 80 nm. A Raith150 electron-beam lithography system is then used to transfer the waveguide patterns to the PMMA. A solution of MIBK:isopropanol=1:3 is used to develop the PMMA.

The next step is the definition of waveguide sidewalls to a depth of approximately 1 µm. Because PMMA is a poor dry etch mask, a 20 nm thick chromium film is deposited via electron-beam evaporation and selectively removed during the standard liftoff procedure. The chromium acts as a highly effective mask during the subsequent chlorine-based dry etching process, which defines the waveguide sidewalls.

After the chromium mask is removed, the refractive index of the $Al_{0.97}Ga_{0.03}As$ layer below the core is changed from 3.3 to 1.61 by oxidation in a 420°C furnace having a 100 sccm flow of water vapor and nitrogen. The oxidation rate was observed to be constant at roughly 130 nm/min. Successfully fabricated conventionally tapered waveguides are shown in Figure 2.

Results and Conclusions:

We have fabricated conventionally tapered waveguides and characterized their relevant optical properties. Although simulations predicted that these waveguides would have relatively low coupling efficiencies, they are easily fabricated and therefore offer a simple means of validating numerical simulations. As shown in Figure 3, measured coupling efficiencies of conventionally tapered devices agree well with simulations.

Future Work:

We are refining the fabrication of inversely tapered waveguides. Once inversely tapered waveguides of satisfactory quality have been produced, we will characterize their optical properties. We will also numerically analyze the misalignment tolerances of our most promising devices.

Acknowledgements:

I would like to thank my mentor, Luigi Scaccabarozzi, for his guidance and patience, Katrin Cox for her many simulations, Michael Deal, Jane Edwards, Maureen Baran, Melanie-Claire Mallison, the SNF staff, CIS partners, and the NSF.

References:

[1] L. Scaccabarozzi, Z. Wang, X. Yu, W.T. Lau, M.F. Yanik, S. Fan, M.M. Fejer, J.S. Harris, Jr., Proc. SPIE, vol. 5355, pp. 111-119 (2004).

[2] I. Moerman, P. P. Van Daele, and P.M. Demeester, IEEE J. Sel. Topics Quantum Electron., vol. 3, pp. 1308-1320 (1997).

[3] M.S. Stern, IEE Proceedings J (Optoelectronics), vol. 135, no. 1, pp. 56-63 (1988).

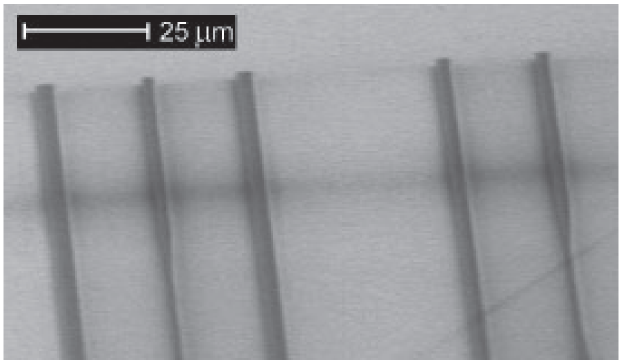

Figure 2: SEM micrograph of conventionally tapered waveguides.

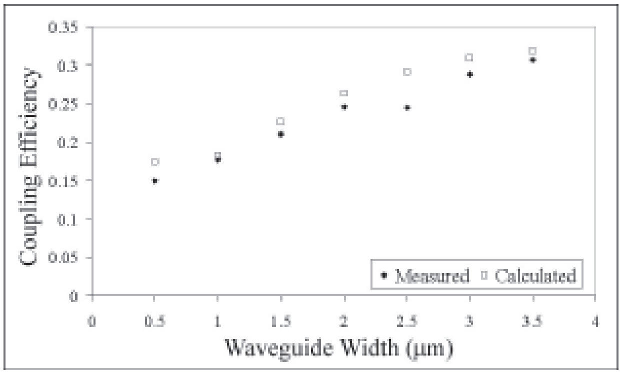

Figure 3: Comparison of measured and simulated coupling efficiencies for conventionally tapered waveguides.