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**ULTRA HIGH CONFINEMENT WAVEGUIDES
FOR
VERY LARGE SCALE INTEGRATED OPTICS (VLSIO)
WITH
THREE DIMENSIONAL PACKAGING**

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ABSTRACT:

By use of high index ratios, Ultra High Confinement waveguides are created. These UHC waveguides make compact devices, sharp bends, and 100,000 electro-optical components per square centimeter, all with three dimensional packaging.

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INTRODUCTION:

By use of very high index ratios between the cladding and guide, Ultra High Confinement (UHC) waveguides¹ can be created, leading to compact devices and sharp bends. Furthermore, with the use of diffractive optics, these Very Large Scale Integrated Optical (VLSIO) circuits² can be interconnected in three dimensional stacks with high density connectivity. A non-uniform grating coupler between a compact waveguide mode and a large Gaussian profile single mode beam is designed and tested. This coupler is a critical component for interconnects, allowing efficient coupling between various beam shapes and compact devices. The size of UHC integrated optical devices is 10 to 100 times smaller per cubic wavelength than present waveguides and resonators, resulting in much higher speed and lower power. These UHC waveguides and components are analyzed using 3D Vector Field Finite Element Methods and microwave scaled experiments.³

ULTRA HIGH CONFINEMENT (UHC) WAVEGUIDES:

In spite of the offered promise of high density integration of optical components, two-dimensional lateral connectivity to date has nowhere approached that of VLSI electronics. We show that by use of high refractive index ratios between guide and cladding, Ultra High Confinement (UHC) waveguides can be created.¹ Ultra High Confinement is defined here as confinement of light in a waveguide with an effective cross-section less than a tenth of a squared free-space wavelength or a resonator volume less than a cubic free-space wavelength (see Fig. 1). Because of the high confinement, a full vector field analysis of the mode is essential for accuracy. A practical implementation of an UHC waveguide in the mid-infrared region uses Ge with refractive index 4.0 on GaAs with refractive index 3.27. The Ge waveguide can be deposited on top of GaAs substrate via UHV E-Beam evaporation. The Ge/GaAs UHC waveguide geometry can scale to the near-infrared as lithography resolution improves to 0.1 μm with the use of GaAs with refractive index 3.6 as the waveguide on AlAs with refractive index 2.9.

Using the numerical analysis³ and microwave experiments we show that a large index ratio confines the light into a waveguide with dimensions as small as fraction of the wavelength of light. Figure 2 shows the electric field profile for the vector component in the vertical direction derived numerically using a cus-

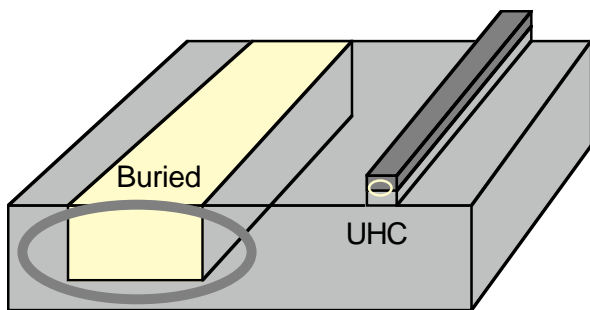


Figure 1. Note UHC waveguides have a mode area (indicated by ellipse) 20 times smaller than the typical buried waveguide.

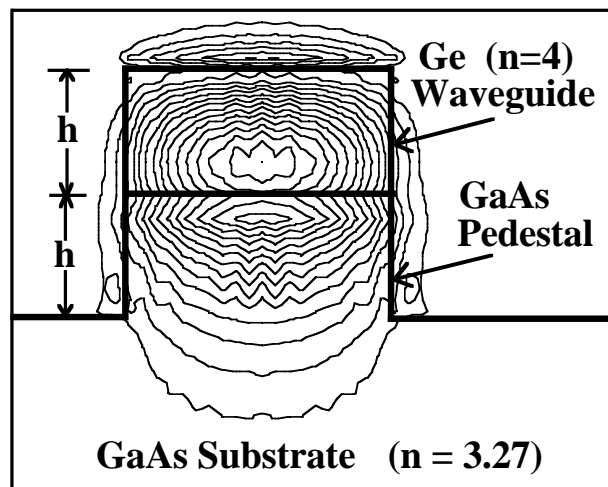


Figure 2. An UHC pedestal waveguide with vertical mode component.

tom (EMFlex) finite element method (FEM) time domain program. An approximate mode was generated and propagated down the guide until steady state was achieved. The effective index of the mode was calculated from the linear phase shift with distance. This procedure was repeated for several ratios of waveguide height to free space wavelength. The new UHC waveguide properties are verified with microwave scaled experiments. Waveguides are created with dielectric materials in the 4 GHz microwave region with the same dielectric constant as Ge (4.0) and GaAs (3.27). Identical propagation experiments are performed using FEM and real microwave waveguides. The effective index, n_{eff} measured in both cases. Note the waveguide size scaling from the microwave to infrared optics is a perfect scaling. The results are shown in Figure 3. These results show good confinement ($n_{\text{eff}} > 3.27$) when h/l is greater than 0.170. In practice, we use h/l between 2.0 and 2.1.

3D COUPLING INTO UHC WAVEGUIDES:

Coupling into the UHC waveguides is a major practical obstacle to their fabrication and testing. The usual buried waveguide mode has relative large size of one to three free space wavelengths that allows direct output from a cleaved edge. In contrast, the UHC waveguide has a dimension that is about 0.2 by 0.3 free space wavelengths, which does not allow efficient edge coupling. Instead, the UHC waveguide for 10 μm light is first adiabatically tapered from 3.7 μm wide rectangular mode to 13.5 μm wide slab mode over a length of 40 μm with 98 % efficiency. This wide mode is then scattered at a 21 degree angle into the substrate with a non-uniform, but periodic grating coupler. The scattering strength of the coupler teeth is continuously increased as the light propagates so as to radiate a Gaussian intensity profile with a diameter of 120 μm . The angle in the substrate is greater than the total internal reflection angle to ensure no radiation to the air side of the coupler. The highly elliptical spot size is then coupled to a round Gaussian profile beam with a diameter of 120 μm by use of an aspheric off-axis elliptical four level Fresnel lens on the back side of the substrate. The 120 μm diameter mid-infrared beam can propagate 2 mm in free space without diffracting, allowing wide tolerance in spacing of the chip stack and allowing over 3000 couplers/ cm^2 to be created.

The large 10 μm wavelength allows periodic but non-uniform grating couplers to radiate a profile better matched to a Gaussian for improved efficiency. The design uses 33 teeth with a 4.5 μm period and two masks with two etch depths of 0.2 μm and 0.45 μm for sufficient range of tooth coupling. The design starts with measure of single tooth scattering coefficients for transmission, reflection, and scatter, including phase shifts. The fully assembled Gaussian coupler is then modeled with EMFlex in two dimensions for a slab waveguide. The output of this coupler was measured for Gaussian diameter and

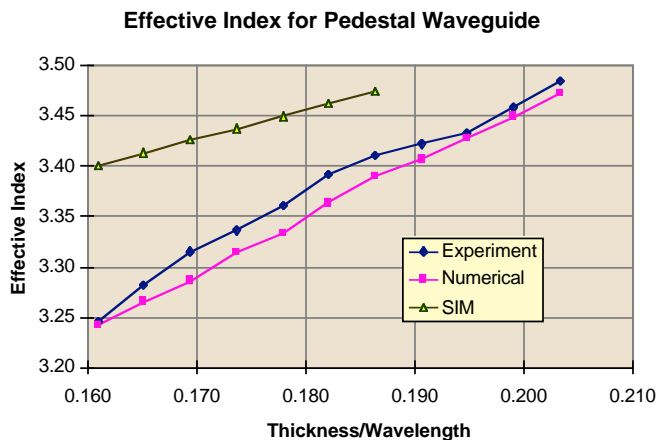


Figure 3. The comparison of FEM, Theory, and Exp.

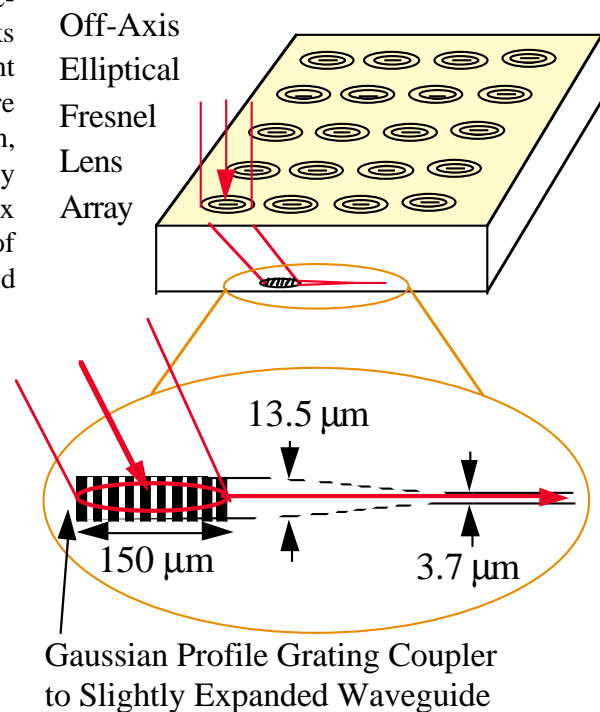


Figure 4. Coupling to UHC waveguide with a normal incidence 120 mm diameter beam.

overlap. The final design had a Gaussian overlap into the desired beam of 85 %. The losses were from scatter to air, backwards scatter down the waveguide, backwards scatter into the substrate, uncoupled transmission in the waveguide, and non-Gaussian components of the scattered beam. Each of these scatter losses are less than a few percent. The coupler uses teeth with a width near that of a half wave in the waveguide because the 1.5 μm width simplifies fabrication and has minimum back scatter down the waveguide (see Figs. 5, 6 and 7).

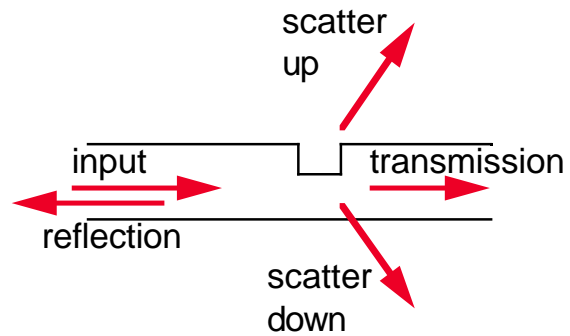


Figure 5. Single tooth model for calculating coupling coefficients.

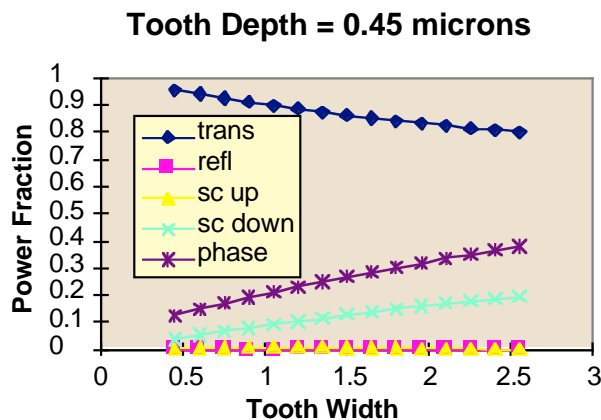


Figure 6. Single tooth transmission, phase shift, and scatter to the substrate for a 0.45 mm depth.

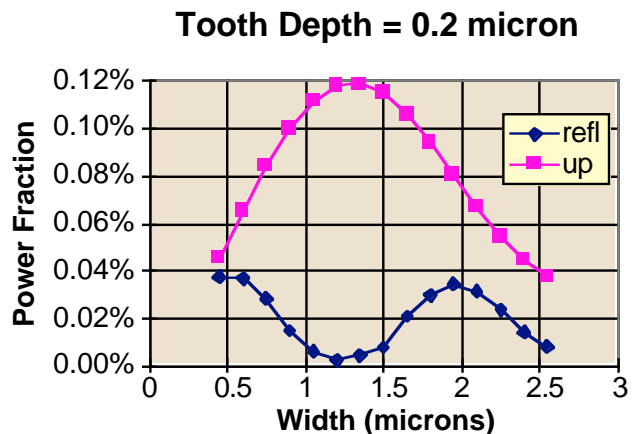


Figure 7. Single tooth reflection and scatter to air expanded for the 0.2 mm deep tooth.

VERY LARGE SCALE INTEGRATED OPTICS (VLSIO):

One of the most significant advantages of the high index of refraction is the ability to create waveguide bends with a radius of less than one free space wavelength. FEM modeling and microwave experiments show that a right angle bend with a radius of 7.5 μm for 10 μm light has a 90% efficiency single mode transmission. This tight bend allows dense components for VLSIO.

The UHC waveguide has several advantages in opto-electronic device improvement due to its small size. We will show the UHC waveguides are capable of creating resonators with volumes less than one tenth of a cubic free space wavelength, 1000 times smaller than VCSELs. The 20 times smaller beam diameter improves gain and other optical properties by a similar factor. The capacitance of the devices is also much reduced, improving the bandwidth of opto-electronic devices to near 1 THz in frequency response. Because of lithography resolution, near-infrared use of UHC concepts may not be viable until the availability of 0.1 mm linewidth lithography.

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