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NON UNIFORM GRATING COUPLERS FOR COUPLING OF GAUSSIAN BEAMS TO COMPACT WAVEGUIDES

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ABSTRACT:

Coupling to compact waveguides can have improved efficiency with use of a grating with non uniform teeth. A combined numerical and mathematical technique for designing this coupler and Finite Element Method results is presented.

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INTRODUCTION:

The beams that emit from lasers are typically have a Gaussian spatial profile. Yet the field profile that emits from a uniform grating is one of a decaying exponential[1]. This fundamental mismatch prevents high efficiency (> 90%) coupling of light into compact waveguides. This limitation has been supported by the difficulty of making high precision waveguide gratings in the near infrared on semiconductor surfaces, especially when non-uniform. However, improved lithography techniques and use of practical devices in the mid-IR overcome these limitations. We discuss a method for understanding and designing grating couplers that may emit beam profiles other than a decaying exponential. Special attention is given to the Gaussian beam profile because of its importance to the laser community and it's minimum diffraction spread. The basic technique is to vary the tooth width along the grating coupler so as to project the desired beam image.

THE DESIGN METHOD:

We use a numerical Finite Element Method[2] to measure the complex amplitude reflection, transmission, and scattered power coefficients for a single mode waveguide for various tooth depths, widths, and geometries. A single mode is injected into a waveguide and scattered off a single tooth within the waveguide. The resultant complex reflection and transmission coefficients into the single mode are measured. The energy difference of these and the original beam is assumed to be the scattered power. A table of these coefficients versus tooth parameters is created. For fabrication simplicity, we typically constrain ourselves to a constant depth tooth so the grating can be fabricated with a single mask and single etch. But actual lithography results, such as a change in etch hole profile for smaller teeth, can and should be taken into account by a substitution of those teeth with their respective coefficients.

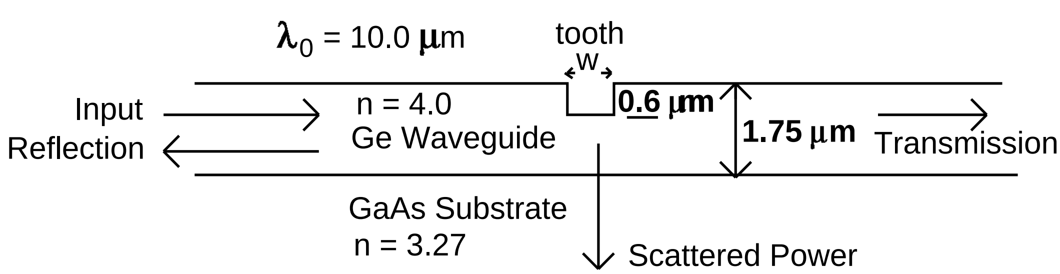
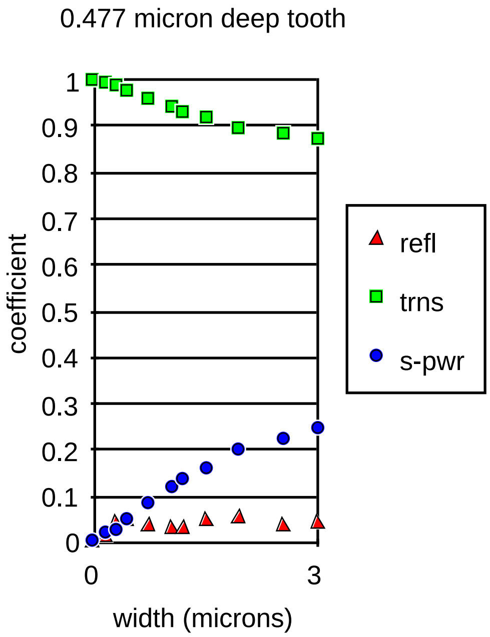


Figure 1: Geometry of scattering problem solved per tooth.

The grating itself will be made of an ensemble of the individual teeth. The tooth spacing will remain roughly constant (this is not a chirped grating) but the tooth size will change. The spacing between teeth can be adjusted to correct for phase changes under the teeth so as to maintain a flat phase profile in the scattered beam, but this is a small percentage of the overall spacing. These



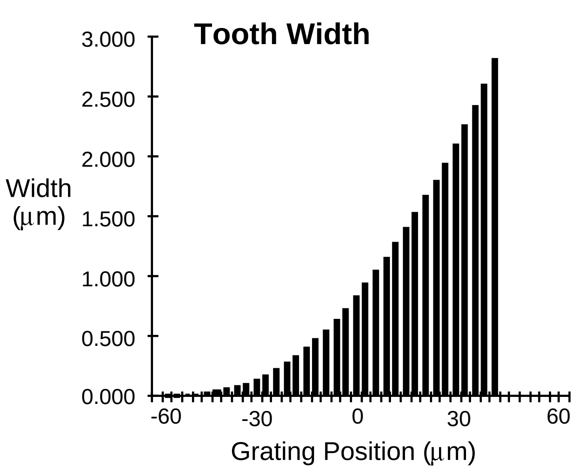
reflection and transmission coefficients are calculated by subtracting the original mode as if there were no tooth and taking the remainder as a change in transmission or reflection caused by the tooth.

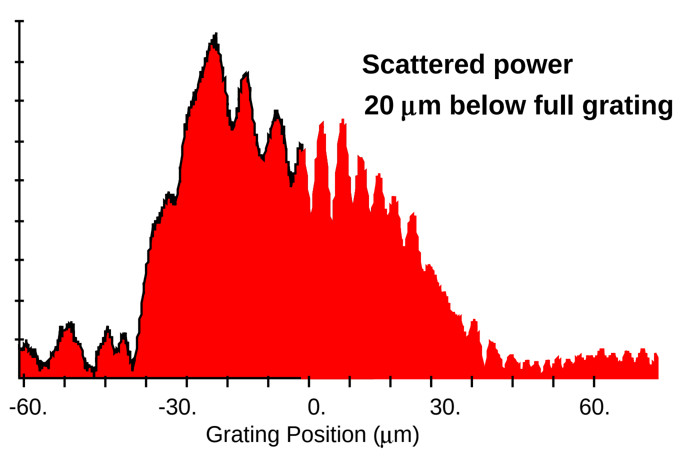
Shown here is a chart of the coefficients for the tooth of Figure 1 with a 0.477 mm deep tooth. Of particular interest is the scattered power versus tooth width. Since the period of the grating is 3.0 micrometers to match the phase period of the waveguide mode, the maximum tooth size is 3.0 micrometers, at which point the waveguide is a smaller unconfined material. The scattered power is almost linear in tooth width with a proportionality of α. The reflection coefficient is almost a constant. We use these assumptions to derive a simple analytic form for the scattered light.

A simple first order derivation of the desired tooth width can be found by assuming the grating is efficient, so that the power remaining in the grating is that which has not been scattered yet. Since the desired scattered power is proportional to the product of remaining power in the guide and the tooth width with constant α, we have the n'th tooth has a size of

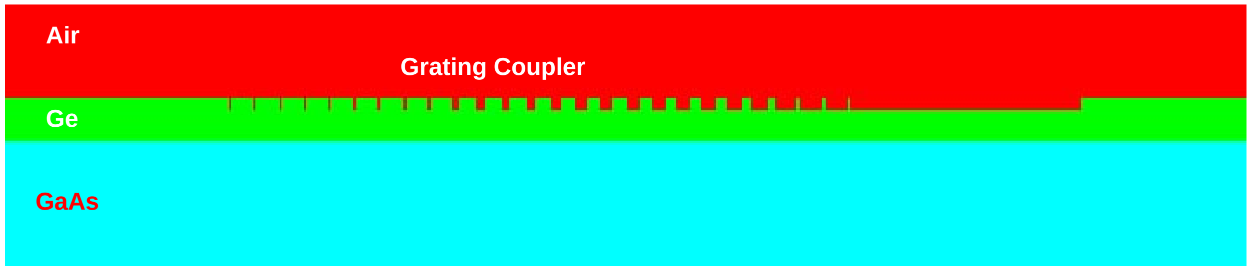
$$w_n = \frac{p}{\alpha} \frac{e^{z^2/z_0^2}}{\int_z^{z_c} e^{z^2/z_0^2}\, dz}$$

where z_c is the cutoff distance of the grating. All light is assumed to be coupled by this distance. The position of the n'th tooth of width w is given by p*n, where p is the period of the grating. This formula gives a tooth function that is shown in the plot below. Note the typical grating has a constant tooth width. The output from the full grating is then determined as show on the lower right. As can be seen, even with a small input tooth coupling, the initial coupling cannot be made sufficiently small to allow weak scattering of the input beam. Also, contact lithography limits us to sizes greater than 0.7 micrometers. Further improvement may require direct e-beam or projection lithography to obtain sufficient dynamic range in coupling per tooth.

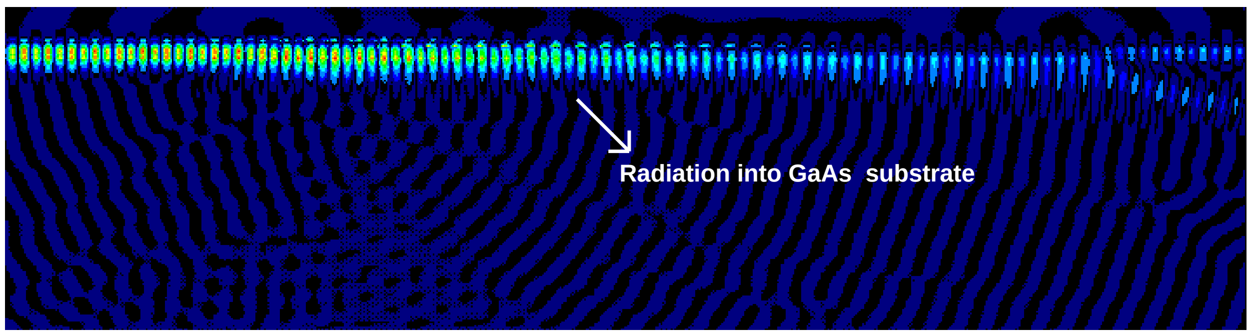




Refractive index profile



SIngle mode Injection → **Field Profile from Finite Element Model**



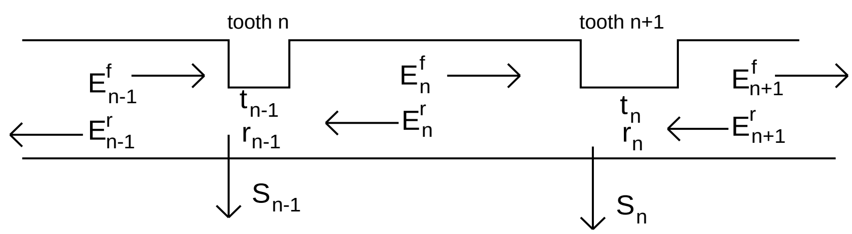
As can be seen from the profile of the electric field component normal to the surface, above, the increased scattering at the beginning of the grating may be from increased field at this point from strong reflection in the latter part of the grating. With modifications to use high reflective properties at the end of the grating rather than the beginning, the profile could be much improved with a decrease in leakage as well.

In addition to the profile limitations from the tooth coupling dynamic range, we also need to limit the back reflection and insure full coupling out of the waveguide. A better design for all these issues can be made with an improved technique. We use the transmission, reflection, and scattering coefficients to develop a matrix formulation of the propagation. For single mode waveguides the field, E_n, just before tooth number n can be deduced from its neighbor teeth with the following approximations:

$$E_n^f = t_{n-1}E_{n-1}^f + r_{n-1}E_n^r$$

$$E_n^f = t_{n+1}E_{n+1}^r + r_{n+1}E_n^f$$

$$S_n = s_nE_n^f + s_nE_{n+1}^r$$



The design then reduces to a system of coupled linear equations. The complex wave behavior at a given inhomogeneous tooth has now been removed. The solution involves perturbing each tooth to obtain a profile closer to a gaussian with lower reflection and leakage out the end of the waveguide. These solutions and status of experiments with Ge on GaAs waveguides will be discussed further.

REFERENCES:

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[2] Wojcik, G., Mould, J. Jr., West, L. C., "Time-Domain Finite Element Modeling of 3D Integrated Optical Devices," Integrated Photonics Research Tech. Digest, W.D.1. Optical Society of America, eds., pp. 112-115, 1993.