An Elegant Grating coupler for high resolution Beam Scanning

Sanam Moslemi-Tabrizi

Carleton University

smoslemi@yahoo.ca

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Overview

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GC Basics

- The basic grating coupler is a periodic structure of teeth and groove with a grating period of d and the coupling angle of θ.
- Because of the periodic structure there will be a leakage process from the waveguide which results in coupling out the light into the free space.
- This leakage process highly depends on the physical structure of the waveguides and grating such as index of reflection of the materials(n_g, n_{cl}, N_{eff}, ...), the groove depth(t_g), the pitch size(d), length of grating (L) and the wavelength of the input light (λ) and even more.
- The leaky wave consist of an infinite space harmonic waves with a complex propagation of $k_n = \beta_n + i\alpha$ where α is the leakage factor and β_n is the space harmonic propagation constant defined as below [2] and [3]: $\beta_n = \beta_0 + \frac{2n\pi}{d} \quad n = 0, \pm 1, \pm 2, \ldots$
- The radiation angle from the GC to the air is defined by $\sin(\theta_n) = \frac{\beta_n}{k_0} = \frac{\beta_0 + \frac{2n\pi}{d}}{k_0} \quad n = 0, \pm 1, \pm 2, \ldots$

Effective index

- To have a valid radiation angel (θ_n) we should have $|\frac{\beta_0+\frac{2n\pi}{d}}{k_0}| < 1$. We also know that $\beta_0 > k_0$. This conclude that n must be negative.
- Depending on the physical structure there will multiple outgoing beams, however in our application we wanted to have one strong outgoing beam so we design our GC for $n = -1$. Taking into account our spec and following the physics explained in the referred papers we must satisfy the following conditions

$$|\beta_0 - \frac{2\pi}{d}| < k_0 \quad => \quad |N_{eff} - \frac{\lambda}{d}| < 1$$

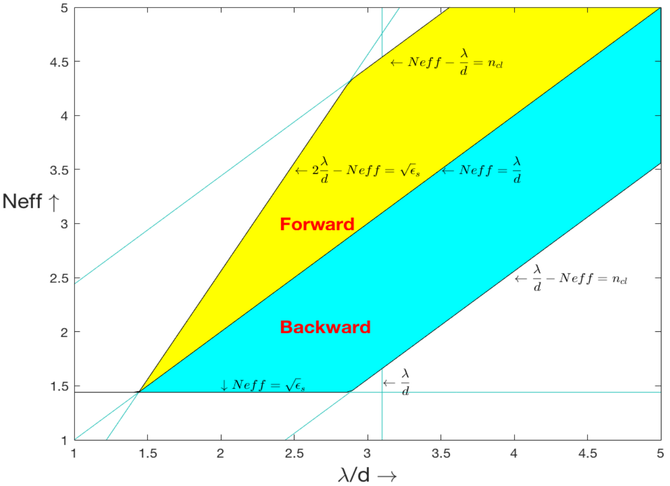
$$|\beta_0 - 2\frac{2\pi}{d}| > k_0 \quad => \quad |N_{eff} - 2\frac{\lambda}{d}| > 1$$

$$|\beta_0 - 2\frac{2\pi}{d}| > k_0\sqrt{\epsilon_s} \quad => \quad |N_{eff} - \frac{\lambda}{d}| > \sqrt{\epsilon_s}$$

$$N_{eff} \neq \frac{\lambda}{d}$$

Effective index valid area

In Figure (1) we showed the region for valid parameters to choose for forward or backward propagations



Narrow beam

- Resolution scanning is defined by $FOV/\delta\lambda_{FWHM}$. So we need to be able to generate a very narrow beam to increase the resolution (lower $\delta\lambda_{FWHM}$).

$$\delta\lambda_{FWHM} = \frac{\lambda^2}{2\pi L N_{g_c}} \tag{1}$$

- To get a narrow beam we need to increase the length and/or increase the group index.
- Increasing the length will increase the transmission loss and also that will increase the size of the device. Also at some point of longitudinal length we will get to the saturation where increasing length won't be effective, because by the most of the light is already saturated.
- With group index, we have more room to engineer the desired material for us using SWG.

Narrow beam (continued)

- The group index is highly depended on the physical features of the grating such as the pitch size, duty cycle and etching depth. Among those the etching depth is process depended variable and there are limitation on it. Non uniform Shallow etching will have a huge impact on N_{g_c} and $\delta\lambda_{FWHM}$, however fabrication for non uniform shallow etching is costly and difficult, therefore we are replacing the effect of etching depth by using sub wavelength grating on the materials to achieve the desired small FWHM. It is proven that using combination of Silicon and Sio2 we can engineer materials with effective index between 1.44 and 3.47 with changing the duty of cycle go SWG.

$$
\begin{aligned}
n_{\parallel}^2 &= f_{swg} n_1^2 + (1 - f_{swg}) n_2^2 \\
1/n_{\perp}^2 &= f_{swg}/n_1^2 + (1 - f_{swg})/n_2^2
\end{aligned}
$$

- For the GC the effective index is dependent on the duty cycle of grating (f) as $N_g = fn_g + (1 - f)n_t$

Low loss

- The duty cycle of the grating and the difference in permittivity of the grating and top cladding effects the leakage factor of the grating. For a rectangular grating this dependency in described as below:

$$\alpha \simeq (\epsilon_r - \epsilon_{cl})^2 \sin^2(\pi f/d) \tag{2}$$

- For minimum loss the index of grating and cladding should be as close as possible (again SWG will help us with that) and also we need to keep away from f=0.5 duty cycle. Again here need would need an optimization for f to have low loss, narrow beam and wider FOV.
- Thickness of grating (t_g) also affects the leakage. Increasing t_g will increase the leakage but at some point we will get to the saturation point where leakage only have small oscillations as shown in figure 2.

Low loss (continued)

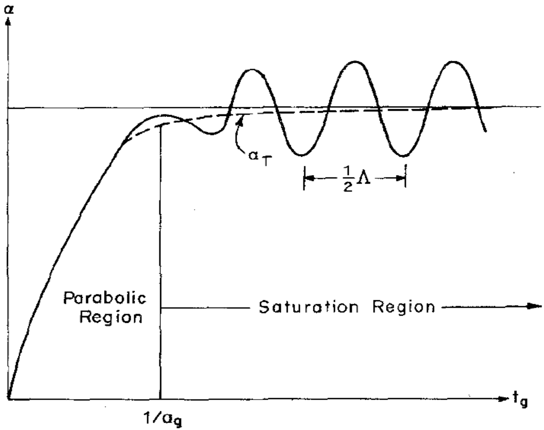


Fig. 8. Typical variation of the leakage α versus the height t_g in a rectangular dielectric grating

Figure: leakagevsthickness

Low loss, grating thickness

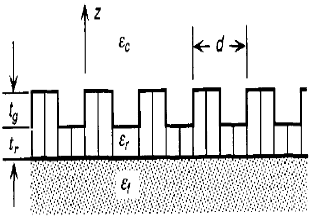
- Following the perturbation analysis for the GC in reference [5] we get to the following points:

$$\gamma_{q_{-1}} = k_0 \sqrt{\epsilon_q - (N - \frac{\lambda}{d})^2}$$

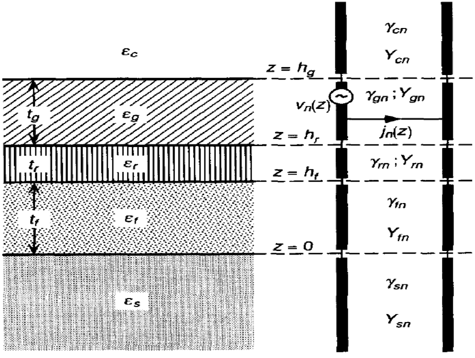
$$\Lambda_{g_{-1}} = \frac{2\pi}{\gamma_{g_{-1}}} = \frac{\lambda}{\sqrt{\epsilon_g - (N - \frac{\lambda}{d})^2}}$$

  - q identifies the layers (substrate, thin film, grating, cladding) (see figure 3)
  - $\Lambda_{g_{-1}}$ is the oscillations period in the saturation region.
  - $t_{g_{crossover}} = \frac{\Lambda_{g_{-1}}}{4}$.
    - $t_g < t_{g_{crossover}}$ is in Parabolic Region
    - $t_g > t_{g_{crossover}}$ is in Saturation Region

Low loss, grating thickness (continued)



(b)



(a) (b)

Fig. 3. Configurations for the perturbation analysis: (a) basic (unperturbed) structure; (b) equivalent transmission-line representation of the periodic (perturbed) structure.

Figure: grating regions

Optimization on GC

- The design of GC involves many parameters, based on fundamental physics of GC we can define some of them but not all.
- We need iterations and choose the based design which can be time consuming
- Using Principal Components Analysis we can reduce he dimension of our variables which will result in reduction of iteration which will save time.

Numerical results

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