0.1 Grating Couplers

Grating couples are being increasingly used in coupling out beams from the waveguides. In the GC structure, the wave propagates through the input waveguide, the periodic structure of the grating area will convert the wave to the leaky wave coupling off the surface of the waveguide to the air. In Telecom industry fiber optics are placed on top of the GC to couple light into it, but we in this research are using free space propagation for the LiDAR application.

The basic grating coupler is a periodic structure of teeth and groove with a grating period of d and the coupling angle of θ. [1]

0.1.1 Choose core material

To analyze the physics of the GC, we start with the wave propagation in the waveguide with a propagation of β_s, 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, the groove depth(t_g), the pitch size(d), length of grating (L) and the wavelength of the input light (λ). Because of the periodic structure of the GC, 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], [3]:

$$\beta_n \,=\, \beta_0 \,+\, \frac{2n\pi}{d} \quad n = 0\,,\, \pm1\,,\, \pm2\,,\, \ldots \tag{1}$$

Obviously the propagation is slower in the waveguide than in the free space for $\beta_s \,>\, k_0$ where $k_0 \,=\, \frac{2\pi}{\lambda}$. Note that usually the leakage factor α is a very small value so $\beta_0 \,\simeq\, \beta_s$ and so we will have:

$$\beta_0 > k_0 (= 2\pi/\lambda) \tag{2}$$

On the other hand according to brag condition the radiation angle from the GC to the air is defined by

$$\sin(\theta_n) = \frac{\beta_n}{k_0} \quad n = 0\,,\, \pm1\,,\, \pm2\,,\, \ldots$$
$$\sin(\theta_n) = \frac{\beta_0 + \frac{2n\pi}{d}}{k_0} \quad n = 0\,,\, \pm1\,,\, \pm2\,,\, \ldots \tag{3}$$

Therefore in order to have a valid 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 $n \,=\, -1$. For this purpose we must satisfy the following conditions:

$$\begin{aligned} |\beta_{-1}| \,&<\, k0 \\ |\beta_{-2}| \,&>\, k0 \end{aligned} \tag{4}$$

Similar for the lower region (substrate) we should satisfy

$$|\beta_{-2}| \,>\, k0\sqrt{\epsilon_s} \tag{5}$$

Note that since $\epsilon_s > 1$ then $|\beta_{-1}| \,<\, k0\sqrt{\epsilon_s}$ is automatically fulfilled. Effective index of reflection (for thin film) is defined as

$$N_{eff} \,=\, \beta_s/k_0 \,=\, \beta_0/k_0 \tag{6}$$

Rewriting equations (4) - (5) we will have

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

or

$$N_{eff} - \frac{\lambda}{d} < 1 \tag{7}$$

$$\frac{\lambda}{d} - N_{eff} > 1 \tag{8}$$

$$2\frac{\lambda}{d} - N_{eff} > 1 \tag{9}$$

$$2\frac{\lambda}{d} - N_{eff} > \sqrt{\epsilon_s} \tag{10}$$

Also to avoid the Bragg condition we must have

$$N_{eff} \neq \frac{\lambda}{d} \tag{11}$$

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

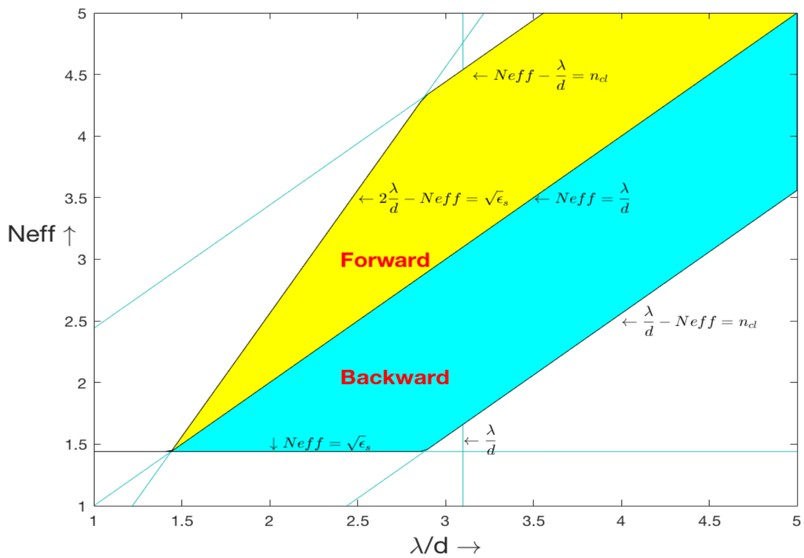

Figure 1: Valid Regions for forward or backward propagations

0.1.2 Generate a Narrow beam (small FWHM)

To achieve a high resolution beam scanning, the outgoing beams must be very narrow. The FWHM of the beam is highly depended to the group index of waveguide core (N_{g_c}) and the length of the grating L as described in equation (12) [4]

$$\delta\lambda_{FWHM} = \frac{\lambda^2}{2\pi L N_{g_c}} \tag{12}$$

To get a narrow beam we need to increase the length and/or increase the group index. However for increasing the length, there are some limitation. Increasing the length will increase the transmission loss and also that will increase the size of the device. The other parameter to get us to a narrow beam is the group index, which 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.

0.1.3 Effect of duty cycle

$$N_g = f n_g + (1 - f) n_t \tag{13}$$

where n_g, n_t and N_g are index values for groove and teeth of GC and the grating area and f is the duty cycle.

0.1.4 Design for minimum leakage

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:

$$\alpha \simeq (\epsilon_r - \epsilon_{cl})^2 \sin^2(\pi f/d) \tag{14}$$

Where ϵ_r and ϵ_{cl} are the permittivity of the teeth and top cladding.

So to keep the leakage at minimum, we need to choose the teeth and top cladding from materials with not too far permittivity values. Here again we can take advance of our SWG design of the materials. We are going to use Silicon photonics platform and we don't have many options for our material selection, but using SWG we can engineer the materials with desired properties.

About the duty cycle we see that the leakage is at it's maximum value at $f = 0.5$. So we need to design the duty cycle to be aways from 0.5.

0.1.5 Design for thickness of layers

The propagation in different region of the structure is given by

$$\gamma_{q_{-1}} = k_0 \sqrt{\epsilon_q - (N - \frac{\lambda}{d})^2} \tag{15}$$

where q identifies the layers (substrate, thin film, grating, cladding). Following the analysis in [5] we know that for small values of t_g (t_g is the etch depth) where $|\gamma_{q_{-1}} t_g| << 1$ then $\alpha d \propto (t_g/d)^2$ meaning the decay is small but highly dependent on etch depth (t_g).
By increasing t_g at some point the decay will be only of small oscillations with change of t_g with a period of Λ_{gn} given by

$$\Lambda_{g_{-1}} = \frac{2\pi}{\gamma_{g_{-1}}} = \frac{\lambda}{\sqrt{\epsilon_g - (N - \frac{\lambda}{d})^2}} \tag{16}$$

For this crossover point we have $t_{g_{cross}} = \frac{\Lambda_{g_{-1}}}{4}$. So for $t_g < t_{g_{cross}}$ the decay is small but highly dependent on the thickness, on the other hand for $t_g > t_{g_{cross}}$ decay only have small variations with changing the thickness.

0.1.6 pic2

The outgoing beam has a FWHM divergence $\delta\psi$ with a ψ_s steering range, the resolution is $\psi_s/\delta\psi$. Based on [6] "To date, OPA steering resolution has been limited. To our knowledge, the widest demonstrated steering range of any OPA was $51°$; however, the beam divergence was relatively large $(3.3°)$[9]. The narrowest beam divergence was $0.3°$; however, the steerable range was relatively small $(0.9°)$[12]. The highest-resolution device had a resolution of 23, achieving the best ratio of steering range to beam divergence ($23°$ and $1°$, respectively) [10]." The highest resolution in 2D using nonuniform etching and 32 emitters is about 23.

We using a simple and fabrication friendly method achieved resolution of 34 by sr

I wrote a MATLAB code where I define my constraints and parameters based on the above analysis and the code will define the physical features of the structure.

References

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