OBJECTIVE: To study mode excitations in planar dielectric waveguide and prism coupling technique. Find waveguide thickness based on number of modes waveguide is supporting and measuring angles of excitations.

BACKGROUND

Dielectric waveguide is the thin film of high refractive index material surrounded by lower index materials. If the light wave propagating in the film arrives to the boundary at an angle which is greater than the critical angle of total internal reflection, the light wave is confined inside the waveguide. The wave components reflected from the top and the bottom boundaries interfere with each other. The interference is constructive if the phase change during traveling across the film plus those due to the reflectance from both boundaries of a waveguide is integer multiple of $2\pi$. In this case, a stationary guided light mode travels along the length of the waveguide with an effective propagation constant and the amplitude of the electromagnetic field varying across the waveguide.

The main parameters characterizing a waveguide are the refractive indices and the film thickness. To determine these parameters we will use the prism coupling technique, where the coupling of a laser beam into a waveguide is governed by the angle of incidence $\alpha$ (Fig.1).

![Prism coupling](image)

Under the certain conditions, the light energy can be transferred into the planar dielectric waveguide by the evanescent field that is excited in the gap between the prism and the film. These conditions are:
- the incident beam must have the proper angle of incidence so the evanescent field in the gap travels with the same phase velocity as the mode to be excited in the waveguide;
- the incident beam must have the same polarization as the mode to be excited;
- the film must be placed close enough to the prism base (typically the gap is in order of half a wavelength).

While changing the incidence angle $\alpha$, the bright lines (so called m-lines because they display the modes of different orders m) appear on the screen only when the laser beam is coupled into a mode of the film. The light propagating in that mode is scattered into the other directions (in the plane of the film) of the same mode and of the other modes. A fraction of the scattered light is then coupled out again by the prism and produces the bright lines on the
screen. In accordance with this explanation it is characteristic for the bright m-lines that they all light up simultaneously when, during rotation of the prism, one of the coupling directions passes through the direction of the input beam. Moreover, in each of these coupling situations, the reflected beam on the screen coincides with one of the m-lines.

Identifying the mode number (m = 0, 1, 2…) and corresponding excitation angle, the film refractive index and thickness can be determined.

**Theoretical Evaluation**

To determine the bounce angles of the waveguide modes we need apply the self-consistency condition of constructive interference for the waves traveling upwards and downwards in the waveguide. It requires that the wave reflecting twice from the boundaries should reproduce itself:

\[ 2kd \sin \theta_m = 2\pi m + \Phi_1 + \Phi_2 \]  

(1)

Here \( k = \frac{2\pi n_2}{\lambda_0} \), where \( \lambda_0 \) is the wavelength of the input light, \( n_2 \) is the film reflective index, d is the film thickness, \( \theta_m \) is the bounce angle inside the film, m is the mode number. \( \Phi_1 \) and \( \Phi_2 \) are the reflection phase shifts at the waveguide boundaries given by the Fresnel equations. In case of TE modes:

\[ \tan \left( \frac{\Phi}{2} \right) = \frac{\sqrt{\sin^2 \Theta - \sin \Theta_c^2}}{\cos \Theta} \]  

(2)

Changing the angles to satisfy waveguide reference (usually bounce angles are measured from the mode propagation direction, not from the normal to the boundary):

\[ \Theta = 90 - \Theta, \quad \Theta_c = 90 - \Theta_c \]  

(3)

we have

\[ (2\pi/\lambda_0)n_2 d \sin \Theta_m = \pi m + \tan^{-1} \left( \frac{\cos^2 \Theta_m - \cos^2 \Theta_{c1}}{\sin \Theta_m} \right) + \tan^{-1} \left( \frac{\cos^2 \Theta_m - \cos^2 \Theta_{c2}}{\sin \Theta_m} \right) \]  

(4)

where \( \Theta_{c1} = \cos^{-1}(n_1/n_2) \), and \( \Theta_{c2} = \cos^{-1}(n_3/n_2) \) are critical angles for waveguide boundaries.

Equation (4) is transcendental equation which can be solved graphically. Each allowed angle of propagation, uniquely defined by the integer m, is referred to as a mode of the waveguide and each mode travels with a particular propagation constant \( \beta_m = n_2 k_0 \cos \theta_m \).

**EXPERIMENTS**

Experimental setup for the light coupling into a planar waveguide is shown in Fig. 2. Light from the HeNe laser is vertically polarized to launch TE modes in the waveguide. The thin film waveguides were fabricated in the ITL at UCSD. S1818 photoresist (from Shipley Co.) was spun on a glass substrate for 30 seconds. This results in a film thickness of approximately 1-2\( \mu \)m, depending on the speed of rotation. The glass slide supporting the waveguide was clamped firmly into the prism coupling assembly. A lens focuses the beam into the prism base. The point where the beam strikes the prism base is the coupling spot. The prism coupling assembly is placed on a rotation stage, allowing varying the angle of the incidence.
Figure 2. Experimental Setup.

A. Prism coupling setup.
1. Make optical setup follow the Fig.2.
2. Verify the 0° setting on the rotation stage: rotate the mount clockwise until the beam reflected from the prism travels exactly backwards through the optical setup to the iris. At this point, the beam would be at normal incidence on the prism surface. The degree marking on the stage should be 45° since the prism is a right-angle prism.
3. Rotate the stage back to 0°. At this point the laser beam is parallel to the waveguide.

B. Coupling into the waveguide modes and measurement of the corresponding coupling angles
1. Rotate the stage with the prism coupling assembly from 0° to 45° and find vertical m-lines. Scan several times through all m modes to establish the number of modes supported by the waveguide.
   As you rotate the prism stage, the coupling into the waveguide modes may become weaker as the optimum coupling point is lost. The coupling strength and the brightness of the modes may be re-optimized by adjustment of the horizontal translation stage with the prism set.
2. Rotate the prism stage from 0° to 45° and measure the angles $\alpha_m$ at which coupling into each mode is observed.
   The results of the measurements should be the table containing the observed modes identified by their numbers $m = 0, 1, 2 \ldots$, and the incidence angle $\alpha_m$ measured for each mode.

C. Calculation of waveguide thickness
1. By tracing the ray $\alpha_m$ coupled into the waveguide calculate the bounce angle $\theta_m$ for each excited mode. Use the reflective indices given in the Fig.1.
2. Calculate the waveguide thickness $d$, substituting $\theta_m$ into Eq. (4). Find an average $d$ for three consecutive modes.

ANALYSIS AND SUMMARY
1. Analyze your results and make comments.
2. Describe what you observe as you rotate the prism. If you are selectively coupling into only one mode at a time, why do you see more than one m-line simultaneously?
3. How many TE and TM modes does this waveguide support?