MOSCOW STATE PEDAGOGICAL UNIVERSITY

# MEASURING THE TRANSMISSION SPECTRUM OF PHOTON INTEGRATED CIRCUITS

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# *Introduction*

**Abstract.** It is difficult to imagine the modern world without optical devices: photo and movie cameras, microscopes and telescopes and many other devices have become an integral part of our life. Powerful and stable lasers, detectors, and optical fibers with a low attenuation coefficient (less than 0.2 dB/km) appeared. This allowed fiber-optic communications to unite countries and continents.

Today, the direction of Photonic Integrated Circuits (PICs) is booming. PICs have received tremendous development as the most promising devices for replacing standard semiconductor chips. This laboratory work is devoted to the study of the characteristics of PICs. As a studied structure, schemes are proposed consisting of: a focusing grating couplers (FGC) and an O-ring resonator (ORR). In this work, you are invited to study one of the simple optical circuits on a chip, while gaining experience on modern scientific equipment.

*Key words: Photon integrated circuits, O-ring resonator, Focusing grating couplers, Fiber array, Fiber optics.*

# *Theory*

## *Snell's law and Total Internal Reflection*

Let's recall Snell's law combining incidence / refraction angles and refractive indices of two substances $n_1$ and $n_2$ (see. Fig. 1)

$$n_1 \sin(\alpha) = n_2 \sin(\beta) \tag{1}$$

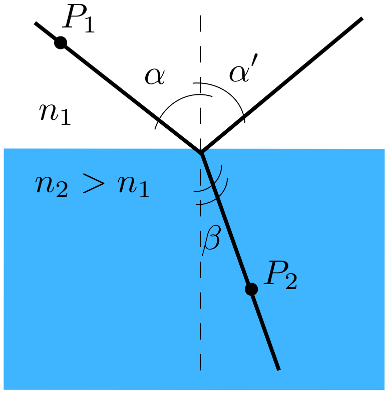

Figure 1: A ray incident on the boundary of two media with different refractive indices is divided into two: reflected and refracted.

This law is not difficult to deduce if we assume that the light passes from point $P_1$ in environment 1 to point $P_2$ in environment 2 in a minimum time. In other words, the sum of the time $t_1$ spent by the light in environment 1 and the time $t_2$ spent in environment 2 is minimal:

$$t_1 + t_2 = \min \tag{2}$$

Also, it is not difficult to prove that the angles $\alpha$ and $\alpha'$ are equal. We can determine the critical angle $\alpha_c$ of the incident beam at which the refracted angle $\beta$ is equal to 90 degrees:

$$\sin(\alpha_c) = \frac{n_2}{n_1} \tag{3}$$

Let's look at a specific example with the following values:

1. $n_1$ - Silicon with $n$ = 4@1,5$\mu$m
2. $n_2$ - Air with $n = 1$
3. $\alpha = 30^\circ$

It is easy to see that in this case the $\sin(\beta)$ will be more than one. From a mathematical point of view, we have an incorrect equality, but from a physical point of view, this means that angle $\beta$ does not exist. So, in this case, the entire incident wave will be fully reflected from the boundary of the two materials. This phenomenon is called: **Total Internal Reflection**. Based on this effect, optical fibers work. Besides, we can make sure that the core of fibers must have a higher refractive index than the environment.

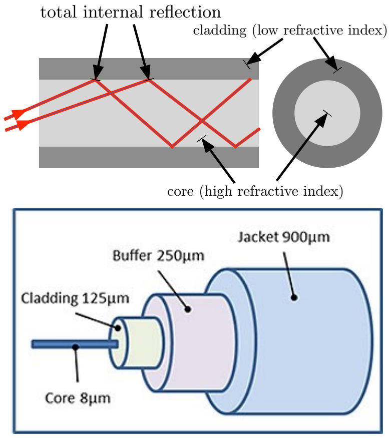

Figure 2: Schematic illustration of an optical fiber. (Top) Propagation of rays in a fiber with different angles of total internal reflection (different modes). (Bottom) Section of a standard optical fiber for telecommunication wavelengths..

## *Optical waveguids*

Optical fibers typically have a circular cross section, but there are also devices with a rectangular cross section, which are called **waveguides**. Examples of planar optical waveguides can be seen in the figure 3. In such waveguides, light also experiences total internal reflection and propagates along the waveguide. At the same time, we can rotate the waveguide, split it, place another waveguide next to it. All this allows us to manufacture various optical devices on an optical chip. Various materials can be used as light-bearing layers: $Si$, $Si_3N_4$, $InP$, $GaAs$ etc.

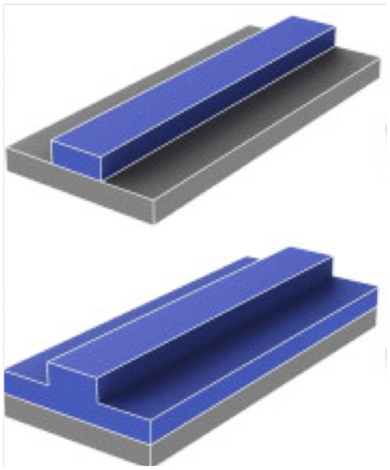

Figure 3: Examples of simple planar waveguides. The light-bearing layer is highlighted in color.(Top) Ridge waveguide (Bottom) Rib waveguide

## *Planar Optical Ring Resonators I*

Planar optical ring resonators (ORRs) are very powerful devices for different applications, including optical filtering, biology, photon pair generation and generation of high-dimensional entangled quantum states. One of the most important parameters of the ORR are waveguide losses, quality factor (Q-factor) and Finess. To understand how a ring resonator works, let us turn to the principle of operation of the Fabry-Perot interferometer.

### *Fabry-Perot Interferometer*

Fabry–Pérot interferometer (FPI) or etalon is an optical cavity made from two parallel reflecting surfaces (i.e: thin mirrors). Optical waves can pass through the optical cavity *only when they are in resonance with it*. Part of the light is transmitted each time the light reaches the second surface, resulting in multiple offset beams which can interfere with each other. The large number of interfering rays produces an interferometer with extremely high resolution, somewhat like the multiple slits of a diffraction grating increase its resolution.

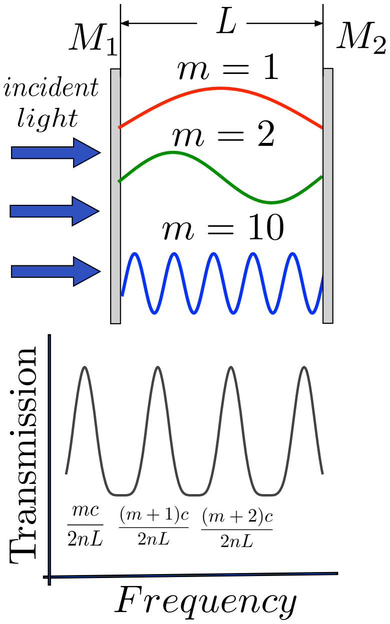

Figure 4: Schematic illustration of the Fabry-Perot optical cavity (Top) and it's transmission (Bottom).

If the beam falls perpendicular to the mirror M1 (see. Fig. 4), the distance between the mirrors M1 and M2 is equal to $L$ and refractive index $n = 1$, then we can determine the resonant wavelengths:

$$2L = m\lambda, \tag{4}$$

where $m$ is an integer.

From Eq. 4 it is obvious that there is a periodicity in the transmission/reflection spectrum of the interferometer. The distance between adjacent resonances (main resonator modes) is called **Free Spectrum Range - FSR**:

$$FSR = \Delta\lambda = \frac{\lambda^2}{L}. \tag{5}$$

## *Planar Optical Ring Resonators II*

Now back to the ring resonator. Such a simple device consists of a waveguide coiled into a circle and a direct waveguide standing next to it Fig 5 and 6.

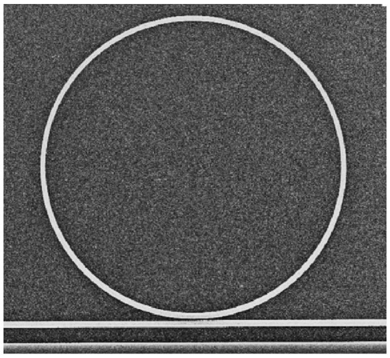

Figure 5: SEM-image of the ORR.

Radiation with a wavelength $\lambda$ propagates along a straight waveguide. In the case when the wavelength is close to the resonance mode of the ring resonator, part of this radiation (Fig. 6) enters the ring (1) , then bypasses in it (2) and returns back to the waveguide (3). In this case, the wave has a phase shift $\Delta\phi$. Thus, two waves, one from Ring resonator and another one in strait waveguide, can interfere together. If the wavelength $\lambda_m$ is an integer multiple of the length of the resonator ($n_g \lambda_m = 2\pi R$; $m = 1, 2, \ldots$ – integer; $n_g$ – is refractive groupe index), then a resonance is observed in the transmission spectrum (here we have destructive interference, $\Delta\phi = \pi$), just like in the case of the Fabry-Perot interferometer.

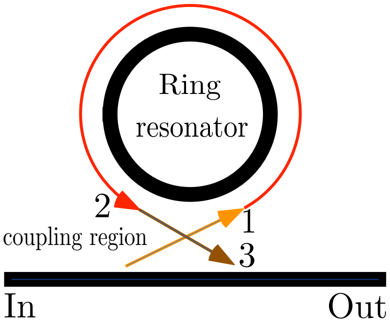

Figure 6: Schematic illustration of the ORR. Part of the radiation enters the ring resonator (1), then envelops it( 2) and returns to the direct waveguide (3), where it interferes with the original wave.

For ring resonators, it is also possible to introduce a Free Spectrum Range, equal to:

$$FSR = \Delta\lambda = \frac{\lambda^2}{n_g L}, \tag{6}$$

Using **Full Width at Half Maximum (FWHM)** of resonance it is possible to determine the **Q-factor** of a ring resonator:

$$Q = \frac{\lambda_c}{FWHM} \tag{7}$$

The Q-factor of the ORR is proportional to numbers of oscillations of the field before the stored optical power depletes to $1/e$ on respect to the initial power: $P(x) = P_0 e^{-\alpha} x$, here $\alpha$ is losses in the ring per unit length:

$$Q\bigg|_{\alpha} = \frac{2\pi n_g}{\alpha\lambda}. \tag{8}$$

In addition, to determine the properties of ORR as a filter, it is useful to introduce the definition of **Finesse**:

$$Finess = \frac{FSR}{FWHM} \tag{9}$$

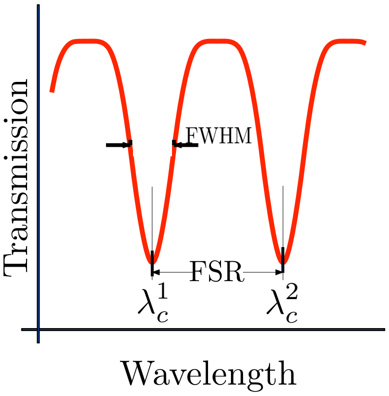

Figure 7: The transmission spectrum of the ring resonator shown in Figures 5 and 6. See the text for explanations.

### *Coupling to PICs*

The main problem of coupling optical fibers and waveguides on a chip is a size mismatch. Single-mode fiber has a core with a diameter of $\approx 9\ \mu$m. To ensure the operation of the silicon nitride waveguide at the telecommunication wavelength in the single-mode, it's cross section is $\approx 1 \times 0.4\ \mu$m.

To solve this problem, Focousing Grating Couplers are made on the chips. Such devices consist of a periodic structure in the form of separate waveguides. Each of these waveguides is a sector of the ellipse, and all of them have one common focal point. Thus, the radiation incident from the fiber, being reflected on each sector of the ellipse, is focused at one point at which the input waveguide of the optical circuit is located.

Since the FGC has a periodic structure, the Bragg condition is fulfilled for it and leads to the fact that such devices have maximum efficiency at a certain wavelength and sensitivity to the direction of polarization of the incident radiation.

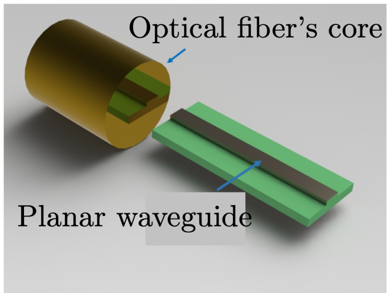

Figure 8: Comparison of the sizes of an optical fiber and a planar waveguide, in a single-mode at a telecommunication wavelength.

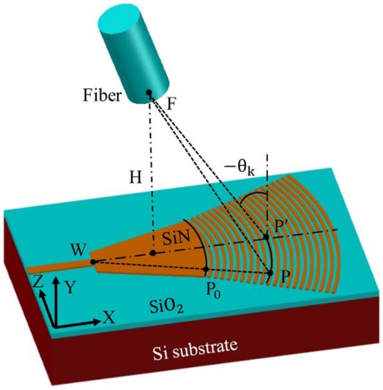

Figure 9: Focousing grating coupler for high efficiency coupling between the silicon nitride waveguide and an optical fiber. */Taken from article: A high-efficiency grating coupler between single-mode fiber and silicon-on-insulator waveguide Rongrui Liu-Yubing et. al. - Journal of Semiconductors - 2017/*

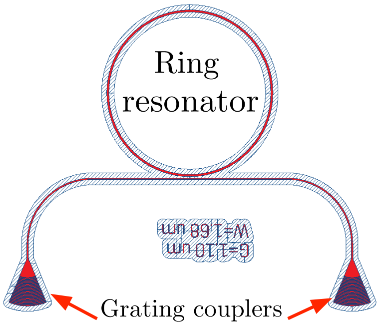

Figure 10: Image of an optical ring resonator with focusing gratings couplers made on an optical chip.

# *Practical part*

## *Experimental setup. Overview*

Equipment:

1. Tunable laser source (New Focus TBL-6600)
2. Polarization controller (Thorlabs)
3. 3D mechanical stage with piezo motors
4. Fast photodetector (Hammamatsu… )
5. Single-mode optofibers (SMF-28e)
6. Microscope
7. Array of optical connectors
8. Fiber array
9. PXI
10. PC

The experimental setup (see Figure12) includes tunable laser source (New Focus TLB-6600) for tune the light in the range of 1510÷1620 nm, polarization controller for adjusting polarization, 3D mechanical stage with piezo motors for precision geometrical aligning of FGCs and light from fibers array, as well as a fast photodetector for optical power measurements.

## *Chip placement and alignment*

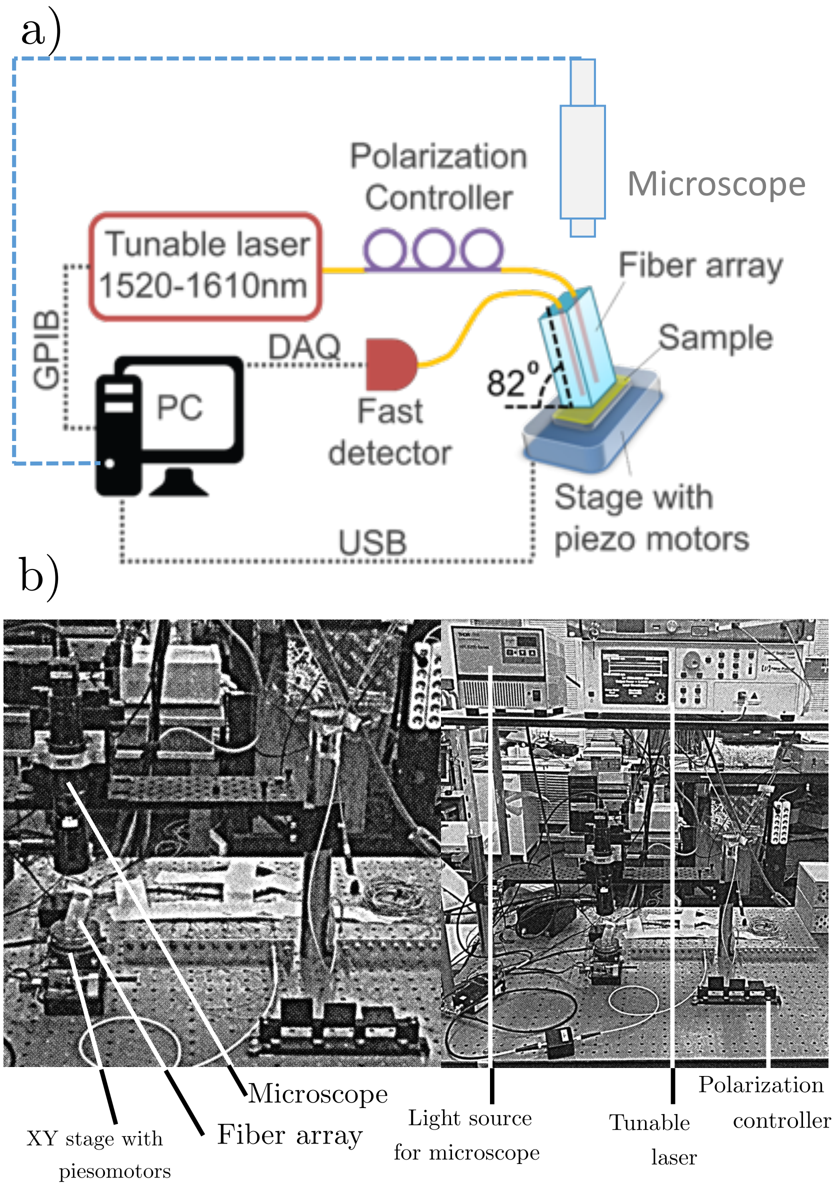

Figure 11: Experimental setup for the measurements of the transmission spectra of ORRs. Light from the tunable laser source is aligned with the ORRs using a fiber array and 3D stage with piezo motors. Light, passing thought structures, was detected by a fast photodetector. The photodetectros signal was recorded using a NI DAQ system. A polarization controller serves to match the the direction of polarization of the incident wave and the FGC. **a)** Schematic view. **b)** General view photo

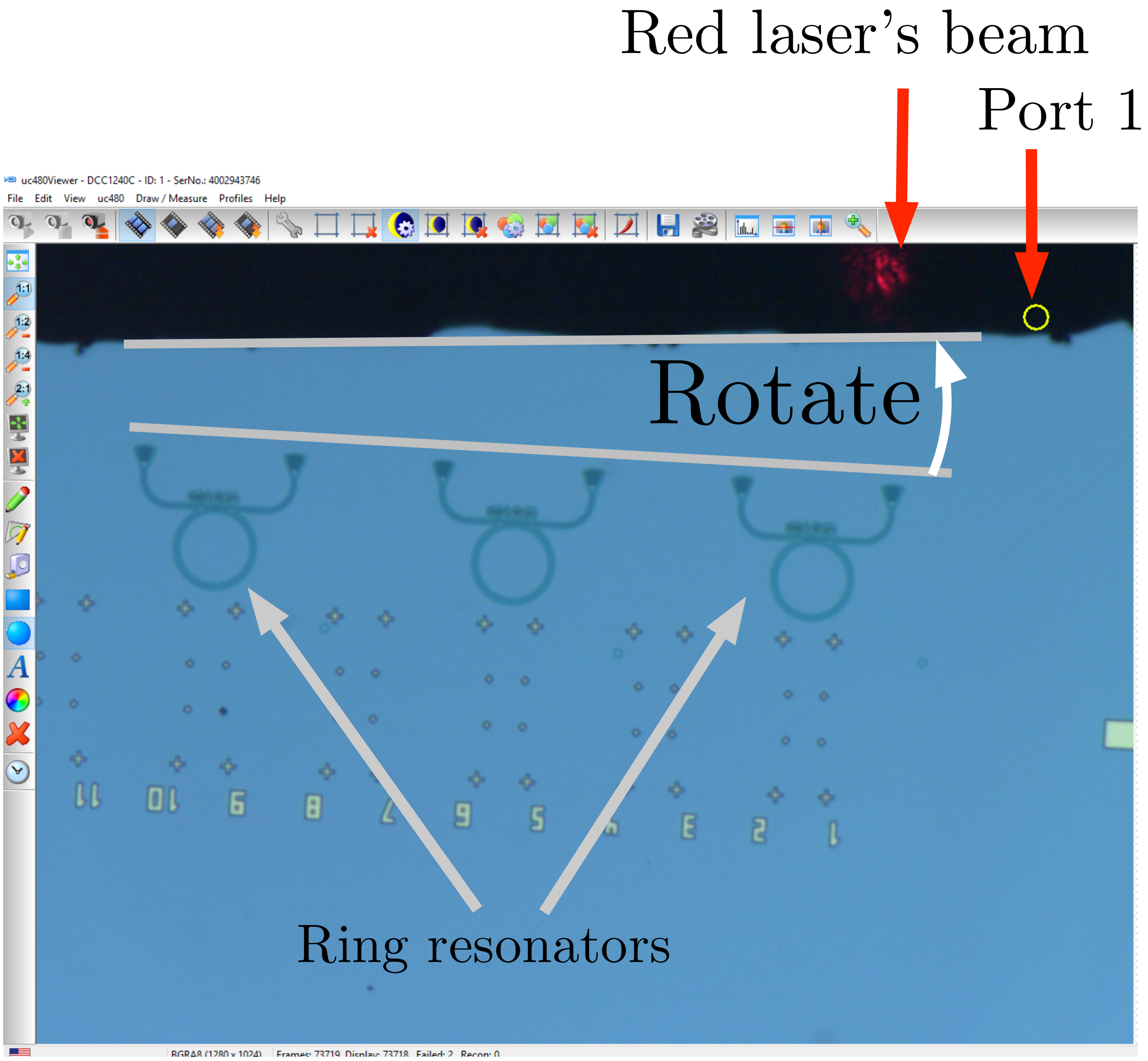

Figure 12: Image from a microscope. One port of the fiber array is already defined and highlighted in a circle. The second port is highlighted with a laser pointer.

The angle between the FGCs and the main line of the array is visible.

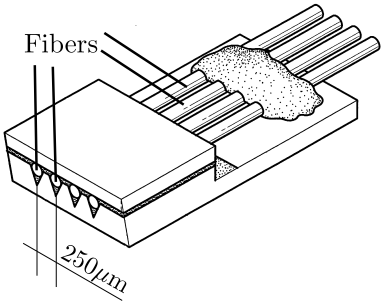

Figure 13: An array of fibers. Fibers glued in V-grooves, the distance between which 250 $\mu$m.

The input/output of radiation to the chip is carried out using an fibers array and gratings on the chip (see Fig. 10 and 13 ). The fibers are glued into the array so that the distance between them is 250 microns. At the same distance from each other are input / output FGCs on a chip.

## *Tasks*

1. Study the experimental setup scheme shown in Fig. 12.
2. Put the chip on the table, than gently with tweezers, move it under fibers array.
3. Using the image from the microscope, align the angle of the chip with respect to the line of the array.
4. Make sure that the laser has a wavelength of 1550 nm.
5. Using piezo motors, tune to maximum transmittance.
6. With the polarization controller, find the maximum photodetector signal.
7. Get the transmission spectrum of the ring resonator with gap=$G_1$ and write it to a file.
8. Starting from step 5, get the transmission spectrum for rings with a different gaps, but with a fixed ring's waveguide width.
9. Open the resulting file in OriginPro and build a graph.
10. Using any method, determine the Q-factor and Finesse of the ring resonator at a wavelength close to the maximum transmission of the entire optical circuit.
11. Fill in table 1
12. Build a graph of the Q-factor and Finesse depending on the gap.

Table 1: Table with the obtained experimental data

| Gap, nm | Wavelength, nm | FWHM, pm | Q-factor | Finesse |
|---|---|---|---|---|
| • | • | • | • | • |

# *Questions*

1. Write a detailed step-by-step description of the transmission spectrum measurement.
2. What is the difference between resonators and interferometers?
3. Derive Equation 4, for the case when the radiation falls on the interferometer F-P at an angle $\alpha$ and refractive index $n > 1$.
4. Calculate the losses per one FGC, provided that the incident power is 0 dBm, the transmitted power is 1 $\mu$W.
5. Find at least 2 errors (mistakes) in this description (manual).