An Archetype Semi-Ring Fabry-Perot (SRFP) Resonator

Shervin Taghavi-Larigani, Jakob VanZyl

[1]Jet Propulsion Laboratory, California Institute of Technology 4800 Oak Grove Dr.

Pasadena, CA 91109, USA

Correspondence author, e-mail: shervin.taghavi@jpl.nasa.gov

***Abstract*—- We introduce and demonstrate the generation of a novel resonator, termed Semi-Ring Fabry-Perot (SRFP), that exhibits unique features, such as, its use of one plane mirror, allowing the SRFP to be easily fabricated as a symmetrical device. In addition to its unique features, it exhibits advantages of ring and Fabry-Perot resonators: 1) compared to a ring resonator that only allows a transmitted intensity, the Semi-Ring Fabry-Perot (SRFP) supports standing waves, allowing both a reflected and transmitted intensity; 2) the reflected light spectrum of the SRFP resonator is much narrower than similar Fabry-Perot, implying higher finesse.**

***Index Terms*—Novel resonator, Fabry-Perot, ring, SRFP.**

I. INTRODUCTION

The basic concept of a resonator is based upon feedback that guarantees the repetition of an event. At the root, there are two ways of obtaining such feedback. The first consists of forcing the feedback through a constraint. Due to this feedback, the same event repeats periodically. This is the case of a Fabry-Perot resonator. Another way of arranging such a feedback is by assuring that the event repeats by tracing its path. This can be obtained if the path shape is closed. An example of such a structure is the circular shape used in a ring resonator. In this paper, we present a novel resonator that incorporates the advantages of the first and the second types of resonators, while having unique new features. This new resonator is termed the Semi Ring Fabry-Perot (SRFP). In order to understand the unique features, we focus in the field of optics, which exemplifies resonance of waves.

A. The first type of resonator (example of a Fabry-Perot resonator)

The most basic type of optical resonator is the Fabry-Perot cavity resonator, which is the archetype of optical devices and is comprised of two parallel reflective planes separated by a distance L. The transmission and the reflection spectrum periodicity of the Fabry-Perot resonator are called the Free Spectral Range (FSR) and are inversely proportional to the length of the cavity. That means in order to separate well the modes of the structure; we need to have a relatively high FSR. Hence, the length L of the medium dictates the modes of the resonator. However, integration of a Fabry-Perot resonator on an integrated chip requires a technically difficult fabrication procedure. In this case, the chip length must coincide with the length of the Fabry-Perot cavity, which determines the FSR of the (transmission, reflection) spectrum intensities. The Fabry-Perot could have a relatively high finesse intensity transmission but has a low finesse reflection transmission. So in summary, the Fabry-Perot exhibits two main disadvantages; difficult integration on a chip, and low finesse intensity reflection.

B. The second type of resonator (example of a ring resonator)

One way to improve the integration of a Fabry-Perot resonator on a semiconductor chip is to use a ring resonator, which does not require the use of any cleaved facet (and which the microsphere is just a three dimension version of it). Ring resonators establish resonance in a similar manner to the Fabry-Perot resonator. The critical distance in a ring resonator is defined by the circumference of circular waveguide rather than the separation between two reflective planes as in a traditional Fabry-Perot resonator. The use of ring resonator is often complicated by the need of multiple coupling regions due to the fact that the device can only guide a progressive wave. Indeed, there is no back reflected field in the configuration where the ring is coupled to a waveguide. Thus, the advantage of a ring resonator over the Fabry-Perot is its ease of integration, but its disadvantage is that it does not reflect back any field, unless non-linearties in the medium are used.

C. Semi-Ring Fabry-Perot Resonator (SRPF)

Here we propose a new resonator. This optical resonator (SRPF) consists of a medium including an edge forming a reflective facet and a waveguide within the medium, where the waveguide contains opposing ends formed by the reflective facet, figure 1 (c), [1-2]. The High reflection facet should be

[1]This research was partly carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration (NASA)

located in such way that it does not interrupt the main waveguide; otherwise it is not an SRFP resonator. That means that the high reflection facet (HR) of the SRFP resonator should not interact with the main waveguide.

II. Advantages of the SRFP Resonator (over a Conventional Ring or Fabry-Perot Resonator)

A. Advantages of the SRFP resonator over a ring resonator

• The SRFP resonator supports standing waves, which allows a reflected intensity in addition to a transmitted intensity, whereas in the case of the ring resonator there is just a transmitted intensity.

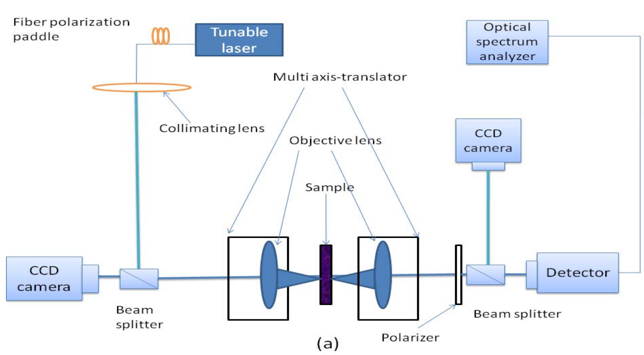
• In the case of a ring resonator and an SRFP resonator having the same length, the same loss, and the same coupling region, the transmission intensity of the SRFP would have a higher extinction ratio. The extinction ratio is the ratio of the power at its maximum over its power at its minimum.

• In transmission, even without any loss, the SRFP transmission spectrum exhibits resonant modes, whereas in the case of a ring resonator, without any loss, the transmission spectrum is a flat band.

B. Advantages of the SRFP resonator over a Fabry-Perot resonators

•The reflected facet of the SRFP does not interact both with the input waveguide and the output waveguide, whereas in the case of the Fabry-Perot the reflected facets result from the discontinuities between the (input, output) waveguides and the resonant medium. This simplifies the fabrication of the resonator, whose length now can greatly differ from that of the chip. Thus the Free Spectra Range of the SRFP resonator is not strongly dictated by fabrication requirements, as in the case of conventional Fabry-Perot resonators. The reflected light spectrum of the SRFP resonator is much narrower than a similar conventional Fabry-Perot, implying higher finesse, figures 2 (a) and (b).

•The use of one plane mirror for both reflecting facets instead of two in the case of the Fabry-Perot.



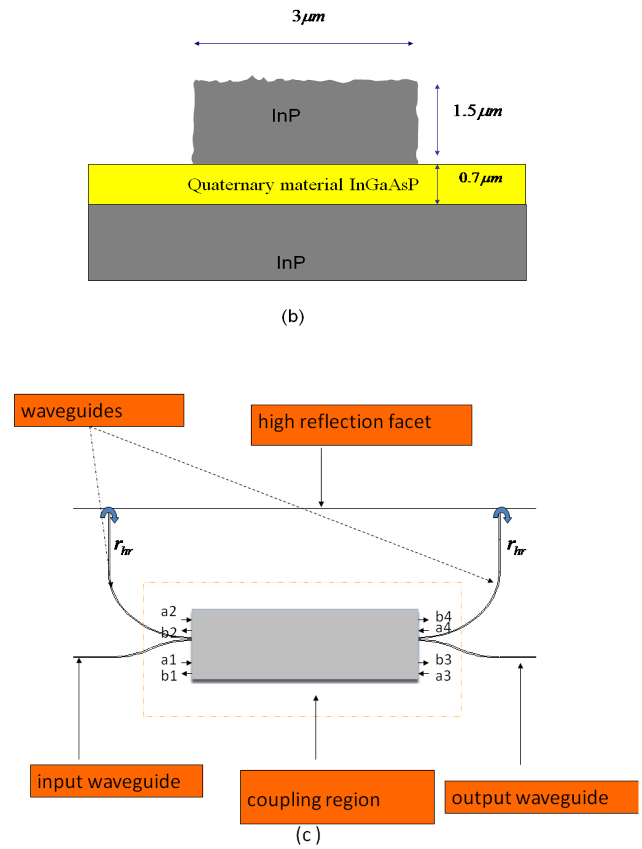


Figure 1:(a) Setup used to test the device; (b) Cross section of the waveguide. (c) An SRFP resonator associated with the modeling of the coupling region the a_i are the input complex field to the coupling region, whereas the b_i are the output complex field.

C. Unique features of the SRFP

• The reflected light spectrum of the SRFP is a frequency “comb”. The separation between two consecutives comb could be changed in function of the optical length of the resonator, whereas in the best case of a grating structure, the reflection spectrum is similar to a comb (but not exactly a comb). The reflected frequencies are harmonic of each other.

• The use of one plane mirror implies that the SRFP can be very easily fabricated as a symmetrical device. This implies that the reflected and the transmitted field to be in quadrature of phase, and therefore orthogonal to each other, [1]. This feature has many applications, especially in the field of communications.

• The delay time of light in the SRFP could be higher than similar Fabry-Perot or ring resonator, [1]. This could be understood by the high degree of interference happening in the SRFP.

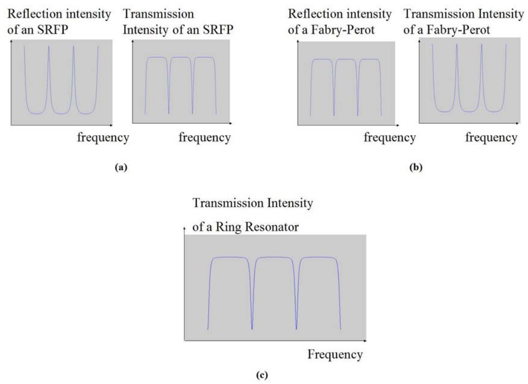


Figure 2: (a) Reflection and transmission intensity spectrum of a Fabry-Perot resonator; (b) Refection and transmission intensity spectrum of a SRFP resonator; (c) Transmission intensity of a ring resonator

III. MODELING THE RESONATOR

One would like to model the structure of figure 1 (c), where the a_i are the input fields to the coupling region and the b_i the output fields from the coupling region. Before modeling the entire structure, we are going to model the coupling region. We assume that within the coupling region there is no back coupling, i.e., there is no coupling between the forward field and the backward field. Using the same approach as in [3], we analyze the coupling region, where $a_i\,(b_i)$ are the input (output) normalized complex field amplitude entering and leaving the coupling region. As a result of the assumption that the forward and the reverse fields are not coupled in the coupling region, we can separate the forward and the reverse fields

$$\begin{pmatrix} b_1 \\ b_2 \\ b_3 \\ b_4 \end{pmatrix} = M_1 \cdot \begin{pmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \end{pmatrix} = \begin{pmatrix} 0 & 0 & t_1(f) & k_1(f) \\ 0 & 0 & k_1'(f) & t_1'(f) \\ t_2(f) & k_2(f) & 0 & 0 \\ k_2'(f) & t_2'(f) & 0 & 0 \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \end{pmatrix}, \quad (1)$$

Where f is the frequency of the field, $t_1(f), t_1(f)', t_2(f), t_2(f)'$, and $k_1(f), k_1(f)'\ k_2(f), k_2(f)'$ are respectively the transmission and reflection coefficients of the complex field. We assume that the coupling is exhibits no loss, meaning that there is conservation of energy between the input light intensity and the output light intensity, expressed by the condition

$$|b_3|^2 + |b_4|^2 = |a_1|^2 + |a_2|^2. \quad (2)$$

The condition expressed in equation (2) is fulfilled if the matrix M_1 is unitary. This means the columns and rows of M_1 are orthogonal to each other:

$$t_i(f)' k_i(f) = -k_i(f)' t_i(f). \quad (3)$$

One way of satisfying this equation is:

$$k_i(f)' = -k_i(f)^*,$$
$$t_i(f)' = t_i(f)^*,$$
$$i = \{1,2\}$$

Then

$$\begin{pmatrix} b_1 \\ b_2 \\ b_3 \\ b_4 \end{pmatrix} = M_1 \begin{pmatrix} 0 & 0 & t_1(f) & k_1(f) \\ 0 & 0 & -k_1(f)^* & t_1(f)^* \\ t_2(f) & k_2(f) & 0 & 0 \\ -k_2(f)^* & t_2(f)^* & 0 & 0 \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \end{pmatrix}, \quad (4)$$

and furthermore using,

$$\begin{aligned} a_2 &= e^{-jkL_2} e^{-\alpha L_2} r_{hr} b_2, \\ a_4 &= e^{-jkL_4} e^{-\alpha L_4} r_{hr} b_4, \end{aligned} \quad (5)$$

We can model the reflection and transmission between ports 1 and 3 as illustrated in figure 1 (b), where r_{hr} is the facet field reflection coefficient, $n_2 L_2$ is the optical length of waveguide 2, $n_4 L_4$ is the optical length of waveguide 4, α is the absorption coefficient, and k is the wave vector. We would like to have the expression for the transmitted light b_3 and reflected light b_1 for a given input light a_1. Therefore, we assume that,

$$a_3 = 0.$$

Using equations (4) and (5), we obtain,

$$\begin{aligned} \frac{b_1}{a_1} &= \frac{k_1 e^{-jkL_4} e^{-\alpha L_4} r_{hr} (-k_2^*)}{1 - t_2^* t_1^* e^{-jkL_2} e^{-\alpha L_2} e^{-jkL_4} e^{-\alpha L_4} r_{hr}^2}, \\ \frac{b_3}{a_1} &= t_2 - \frac{k_2 e^{-jkL_2} e^{-\alpha L_2} r_{hr} e^{-jkL_4} e^{-\alpha L_4} r_{hr} t_1^* k_2^*}{1 - t_2^* t_1^* e^{-jkL_2} e^{-\alpha L_2} e^{-jkL_4} e^{-\alpha L_4} r_{hr}^2} \\ a_4 &= e^{-jkL_4} e^{-\alpha L_4} r_{hr} b_4, \end{aligned} \quad (6)$$

Figures 2 (a) and (b) illustrate the transmission and reflection spectrum through the SRFP resonator.

IV. CHOICE OF THE COUPLING REGION

The optical coupler that we used to couple light into the resonator is a 2x2 Multi Mode Interference four-port directional coupler, [4].

V. CHOICE OF THE MATERIAL

The SRFP resonator introduced earlier can be realized in a number of different dielectric materials. In the present work, we focus upon the III-V semiconductor alloy. We use an InP substrate, where a layer of 0.7 µm of InGaAsP, followed by an layer of 2 µm is grown upon it. The ridge waveguide is designed such that just the upper layer of InP is etched, figure 1 (c).

VI. Fabrication

A similar fabrication process described in [5] (to which we add a step of cutting the wafer using ebeam followed by Focus Ion Bombardment, and a step of high reflection deposition) has been used in order to obtain the structure shown in figure 1 (c).

• A 120 um Si etch mask layer was deposited by plasma-enhanced chemical vapor deposition.

• Ebeam lithography and development.

• The PMMA patterns were transferred into etch mask layer. The SiO2 was etched by inductively coupled plasma reactive ion etching (ICP-RIE) using C_4F_8 plasma.

• The remaining PMMA was removed with a gentile plasma etching step.

• The patterned layer then served as a hard mask for transfer into the active membrane, using a low voltage ICP-RIE Hydroiodic acid to etch the InP layer.

• In our specific application we do not need to remove the SiO_2 since it can be used as a protection layer and does not change the optical beam. If we would like to remove it, we can use a buffered hydrofluoric (HF) acid solution.

• Lapping.

• Cutting the facet using ebeam followed by focus ion beam (FIB) technique

• HR coating deposition.

Figure (3) illustrates a fabricated SRFP.

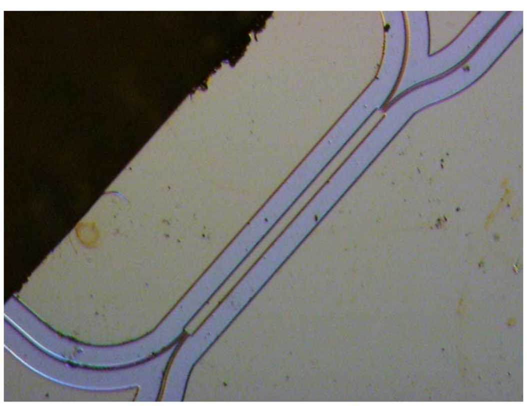


Figure 3: Picture of a fabricated SRFP

VII. Initial Tests

The optical setup shown used to characterize the SRFP is shown in figure 1 (a). A tunable laser ranging from 1440 nm to 1640 nm and delivering few milliwatts was used. The laser is used in automatic mode and sweeps the entire range at a speed of 5 nm/s. The laser is coupled to single-mode fiber. The polarization of the light inside the fiber is controlled with a set of fiber paddles. The light coming out of the fiber is then collimated for free space. A linear polarizer is used to select the correct polarization. The light is then coupled into the waveguide facet of the device through an aspheric lens (50-60)X (NA=0.65). Another aspheric lens is used to collect light from the resonator. For careful positioning of the lens' focal plane, relative to the input and output facets, the lens are mounted on a micrometer translation stage. The micrometers have five axes and a resolution of 0.02 µm. For optimizing the input and output coupling conditions, an infrared camera is useful for viewing the optical mode profile. In order to measure the transmitted light through the device, a photo detector is placed at the output. The entire optical tool used had an antireflection (AR) coating for the range of wavelength of operation. Figure (4) depicts the normalized (transmission and reflection) spectrum of the SRFP.

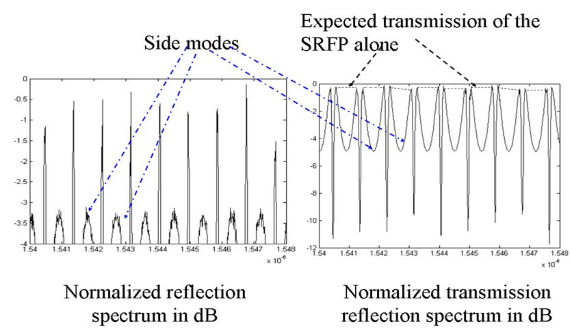


Figure 4: Normalized reflection and transmission intensities spectrum of a SRFP in dB, the side modes result from the discontinuity created by the cleaving of the chip (they are not from the SRFP).

VIII. Acknowledgment

We are grateful to R.L. Tjoelker for his comments and feedbacks.

References

[1] S. Taghavi Larigani, "Theory, Fabrication, Testing and Applications of a Novel Archetype Semi Ring Fabry-Perot (SRFP) and a New Tiltmeter", PhD thesis California Institute of Technology 2006.

[2] United States Patent Serial No. 11/225,832 by Taghavi-Larigani, Shervin; et al. "Optical Resonator".

[3] A.Yariv, "Universal relations for coupling of optical power between microsenators and dielectric waveguides," Electronics Letters, Vol. 14, No. 4, 2000.

[4] L. B. Soldano, F B. Veerman, M. K. Smit, B. H. Verbeek, A. H. Dubost, and E. C. M. Pennings, "Planar Monomode Optical Couplers Based on multi-mode Interference Effects," Journal of Lightwave Techno log y, Vol 10, No 12, 1992.

[5] W. M. J. Green, R. K. Lee, G. A. DeRose, A. Scherer, and A. Yariv, "Hybrid InGaAsP-InP Mach-Zehnder racetrack resonator for thermooptic switching coupling control," Optics Express,Vo. 13, No. 5, 2005.