Design of a Wavelength-Meter with Measurement Range up to 100nm and 8 pm precision

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Hereby, we present a new design for an integrated wavelength meter. The device works by coupling an unknown monochromatic light source to four microring resonators of different free spectral range containing a phase modulator. The output of each ring is coupled to a separate photodiode (PD). The setup relies on modulating the spectral position of ring resonances while monitoring transmitted power with PDs. Thanks to data acquired during calibration, is possible to relate such output powers to a unique wavelength. While state-of the art designs allow for either high precision or broad range, our system does not require any tradeoff between those two characteristic, achieving up to 8 pm precision (for a ring Q factor equal to $2*10^5$) and 100 nm of wavelength range. We will discuss how losses influence the measurement speed and the resolution of the device. The structure, although platform independent, will be realized in InP.

Introduction

Over the recent years, development of integrated wavelengthmeters has drawn significant attention from the scientific community [1]-[4]. Miniaturized wavelength meters are employed in numerous applications, such as Wavelength Division Multiplexing, spectroscopy, metrology, and operational control of tunable lasers[1]-[2]. State of the art integrated wavelength meters centred at *1550nm* wavelength have either very narrow bandwidth and high precision (*5nm, ± 8pm*)[1],[4] or increased operation bandwidth compromising the resolution (*40nm, ± 0.075nm*)[3]. We present here a method to increase the operational bandwidth of ring resonators based wavelengthmeter maintaining a high accuracy limited by the Full Width Half Maximum (*FWHM*) of the resonators. Designs in literature have been realized in silicon nitride (SiN) or silicon (Si) material systems. Those two materials are very popular, however neither of them allow for straightforward laser integration[5], with the addition that in SiN fast phase modulators are still missing. For this reason, we choose the generic Indium Phosphide (InP) platform of the Franhofer Heinrich Hertz Institute, HHI for simulating and fabricating our prototype. InP platforms enable higher operation speeds and gives future prospects of integration into a more advanced photonic system. The design idea, although, is general and can be implemented in every platform where modulators are possible. In this paper we present the general theoretical approach to the device and the expected performance of our prototype that is under fabrication. In our design, we achieve maximum operation range by employing four microring resonators that contain phase modulators, each coupled to a separate photodiode (PD). Our setup relies on modulation of spectral position of ring resonances while monitoring the PDs output. Our wavelength measurement is based on checking at which modulator bias the diodes are displaying a minimum of the transmission and comparing it with a lookup table obtained from calibration.

Method

In Figure 1 the schematic of the circuit is reported. An input source is coupled from the left-hand side and guided to four resonant rings in the so called all-pass configuration. In every ring a Phase shifter (PHS) permits to add an extra phase shift θ to the optical path. At the through port of every ring a photodetector is present. The wavelength resonance condition is $i\lambda=2\pi r n_{eff}+\theta(V)$, given λ the wavelength in the cavity, i an integer, r radius of the ring, n_{eff} the effective index of the ring and $\theta(V)$ the phaseshift added. When this condition is fulfilled, a minimum is registered at the photodiode. By changing the phase $\theta(V)$ in the range [0-2π], we obtain a unique subset of wavelengths on resonance with the ring. We can identify Ithose wavelengths with $\lambda_n(I,V)$ where n identifies the ring, I an index that counts the resonance wavelength and V is the applied voltage. The subsets of $\lambda_n(I\ V)$ could be calculated theoretically, However accurate modelling is challenging, so we opted for an external calibration of the system. We will explain the calibration further below. For now, let us assume that we know exactly all the subsets $\lambda_n(I,V)$ for all the possible triplets (n,I,V). When an unknown laser source is coupled in the device, the source is carried to all the rings and the intensity of the light transmitted through the rings is measured at the detectors. PHSs are driven to sweep the phase $\theta(V)$ in the interval $[0,2\pi]$. During this sweep all the 4 detector signals are acquired. All PDs have a minimum in transmission that can be associated with a voltage V_n that makes the wavelength resonate with the ring. Using the calibration database it is possible to obtain the subsets of wavelengths $\lambda_n(I,V_n)$ that resonates with the ring in that specific condition. From the four rings we obtain four different subsets of wavelengths that resonate with the ring in such condition. The intersection of the four subsets determines a unique wavelength that is the input wavelength.

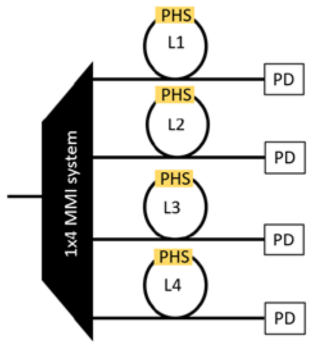

Figure 1: Schematic of the circuit.

Rings design

All the rings are of different length in order to allow for the Vernier effect. It is advantageous to keep the ring length as short as possible. A shorter ring has higher Q factor and consequently a smaller (FWHM), thus improving the resolution of the wavelength-meter. Shorter rings also have a wider free spectral range, thus increasing the operational bandwidth of the device. The all-pass ring configuration has been preferred to the add and drop because it allows to keep the rings shorter and prevents extra losses due to the presence of a drop port. The minimum length of the ring is fixed by a number of design constrains. Every ring must have a directional coupler, a PHS long enough to guarantee a 2π phase shift and two *180* degrees bends with a small radius of curvature. This typically leads to a minimum length in the range *[1-3] mm* depending on the platform. The shortest ring we were able to design in HHI platform has a length of $L_1 = 3318\ \mu m$. With A single ring is already possible to measure wavelengths after calibration[4], but its bandwidth is equal to the FSR of the ring. We can estimate the FSR using the equation:

$$FSR = \frac{c}{n_g L}$$

With our shortest ring and taking $n_g = 3.5$ we expect an FSR close to *25 GHz (0.2nm)* at a central frequency of *193 THz*. By using additional rings however, we can expand the operational bandwidth of the device. Let us consider the following equation that describe the resonant wavelength of two rings:

$$\lambda_n(i) = \frac{(l_1 n_{eff} + \theta_1(V))}{i}$$

In the left part of fig.2 we represent with arrows some of these resonances $\lambda_n(I, V)$. The resonances of the first ring are the arrows characterized with an horizontal bar, the one of the second ring instead by two oblique bars. By changing the phase $\theta(V)$ of each ring we can tune both rings on resonance with the unknown source. In our representation the overlaps of two arrows identifies a possible value of the input wavelength. This new ring lets us expand the operational range of our device. We can compute the new combined free spectral range with [6]:

$$FSR_{1-2} = FSR_1 \frac{L_1}{L_1 - L_2}$$

We have used a second ring with length $L_2 = 3324\ \mu m$ that corresponds to $FSR_{1-2} = 14.3THz\ (100nm)$. However, a new problem arises: the resonance peaks are not perfectly sharp. They have a FWHM that limits the resolution on resonances reading. Knowing the Q factor of the cavity we can derive the FWHM of the peaks as $FWHM = \frac{\omega}{Q}$ where ω is the resonance frequency. Potentially this means that if $(\lambda_1(i) = \lambda_2(j))$ is valid for indexes (i0; j0), it might also be true for the indices $[(i_1,j_1), (i_2,j_2)\ldots]$. We can solve this ambiguity of having only a couple of indexes (i_0, j_0) by adding a ring of length $L_4 = 3578\mu m$. This length has been chosen such that the difference $FSR_1\text{-}FSR_4 > FWHM$. With our lengths this led to *FWHM 1.8 GHz*. Such constrain on the full width half maximum corresponds to having $Q > 10^5$. We can see a visualization of this process in the right part of fig. 2 (not in scale). The joint FSR_{12} covers the full bandwidth of the device and identifies a single region where $(\lambda_1(i) = \lambda_2(j))$. This condition is satisfied for several couples of values of (i, j). With the joint FSR_{14} we can identify the single couples of indices $(i_0; j_0)$ that fulfil $(\lambda_1(i_0) = \lambda_2(j_0))$. However, simulating the device spectral response in VPI, we have seen that three rings are still not sufficient to find a single couple of indexes $(i_0; j_0)$. This has been solved by adding a ring of length $L_3 = 3378\mu m$ and using an identical procedure to remove such ambiguity.

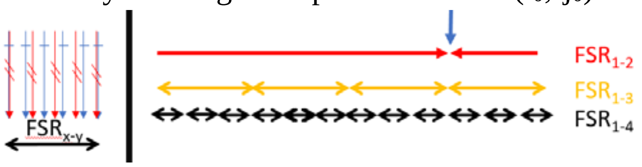

Fig. 2:left side: Arrows represent resonance in spectra with different FSRs. Overlapping arrows identify input wavelength. Right side: different FSR arrows allow to detrermine the input wavelength

Calibration procedure

In order to calibrate the device an external known tunable laser source is necessary that ideally covers the entire operational bandwidth. In practice, even a source with a narrower range can be used and the calibration expanded using a polynomial fit. The laser is swept over the bandwidth and fed to the circuit. Transmission spectra are recorded for every ring. The procedure is repeated for different voltages storing the different acquisitions. This creates a calibration database that can be used to track the resonant wavelengths. Even using few voltage points is possible to use a polynomial fit to predict the resonances for an unknown voltage.

Measurement speed

A ring resonator has a typical cavity lifetime that is determined by the Q factor: $Q = \omega\tau s$. A time $T = 3\ \tau s$ is necessary before considering the ring to be stabilized [7]. To cover the full FSR of any of the rings we need a number of steps in the voltage applied to the PHS. We chose this number of steps (*m*), in order not to lose resolution but also not to over-sample the curve. Given that the limit resolution is equal to the FWHM of the ring:

$$m = \frac{2FSR}{FWHM} = \frac{2FSR \times Q}{\omega}$$

We can express this equation in terms of Q to estimate the time T necessary for a complete measurement as:

$$T = m\tau_s = 6FSR \times \frac{Q^2}{\omega^2}$$

We can notice from this equation that the measurement speed scales with the square of the Q factor In the following table we estimate the speed of our device for different Q factors at constant single ring *FSR = 30 GHz* and *ω= 193 THz*.

Q factor	T	resolution
10^4	500ps	160 pm
10^5	50ns	20 pm
10^6	5μs	1.6 pm

An important remark is necessary, the measurement speed does not depend on the number of rings since all the rings are measured simultaneously.

Conclusions

A photonic-integrated wavelength-meter based on multiple ring resonators has been proposed capable of achieving a wavelength range of *100 nm* at a wavelength resolution of *1.6 pm* for a Q factor of 10^6. Theory shows that the measurement speed scales with the square of resonators Q-factor, while measurement resolution scales inversely proportional with the Q-factor. The possibility of integrating high speed modulators combined with the simultaneous measurement of multiple ring resonators, allows for unprecedented wavelength measurement speeds. The design is currently being fabricated at HHI.

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