Characterization of a MZI based tunable filter using an optimization algorithm

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We present the characterization of a Mach-Zehnder Interferometer (MZI) based tunable filter to achieve stepwise tuning over a free spectral range (FSR) of 10 nm, with a 3-dB bandwidth of 1 nm. The design is a wavelength-selective tunable filter that employs eight reversely biased voltage-driven electro-optic phase modulators (EOPM) to change the phase of the light in the eight arms of a MZI tree. A star coupler is used to achieve the splitting and combining of the light at the filter input and output. The simulated transmission profile is compared to experimental results when the arms are driven through an optimization algorithm. This allows for estimating the contribution of initial dephasing in each arm that can be attributed to phase errors. We show a tuning of 9 nm with 1 nm steps using a Nelder- Mead stochastic search algorithm for voltages. Filter's figures such as pass-band shape and full width half maximum (FWHM) are also estimated. The filter has been realized on the indium phosphide (InP) generic platform, on a multi-project wafer (MPW) run..

Introduction

Tunable lasers are crucial to many applications in datacom and sensing, particularly in dense wavelength division multiplexing (DWDM) [1], gas sensing [2], optical coherence tomography [3] and LIDAR [4]. The key requirements for tunable lasers in these fields are miniaturization, faster speed, large integration capacity and energy efficiency. For this, photonic integrated circuit or PIC-based tunable lasers are particularly interesting.
A core component of an integrated widely tunable laser (tunability >>10 nm) is a tunable mode selection filter. Several types of tunable filters have been demonstrated in monolithic PICs. The state of the art includes ring resonators [1], sampled grating distributed Bragg reflectors (SGDBR) [6] and Mach Zehnder interferometers (MZIs) [7] [8]. Sampled gratings and ring resonator based tunable lasers are promising in terms of wide tunability, with demonstrated tuning ranges above 40 nm [5]. However, for SGDBR structures, the fabrication of complex gratings requires high-resolution lithography techniques like electron beam lithography. In case of ring resonator based filters, the tuning is slow as it employs thermal effects. Furthermore, these types of filters suffer from frequency drift that is attributed to the injection current-based tuning. On the other hand, in the monolithic InP generic platform [9], filters using an MZI-based feed-forward structure employ electro-optic effect-based tuning. This mechanism helps to overcome the heat induced frequency drift problems, and is also potentially faster. Also, compared to DBR gratings, these structures are relatively simple to fabricate. These filters have also exhibited very wide tuning range such as 74 nm, measured by Latkowski *et al.* [10].In this paper we describe the preliminary measurement results of a tunable filter based on MZI feed-forward structure that uses electro-optic phase modulators (EOPM) on each arm of the MZI. The filter is tuned by varying the phase on the EOPMs with reverse bias voltage.
In the first section we will describe the design of the filter and the theory of the tuning mechanism. In the second section we will elaborate on the measurement setup and the optimization algorithm called *Nelder-Mead stochastic search* [11] used to search for the voltage configuration. In the third section we will discuss the obtained results from the experiments in terms of filter performance.

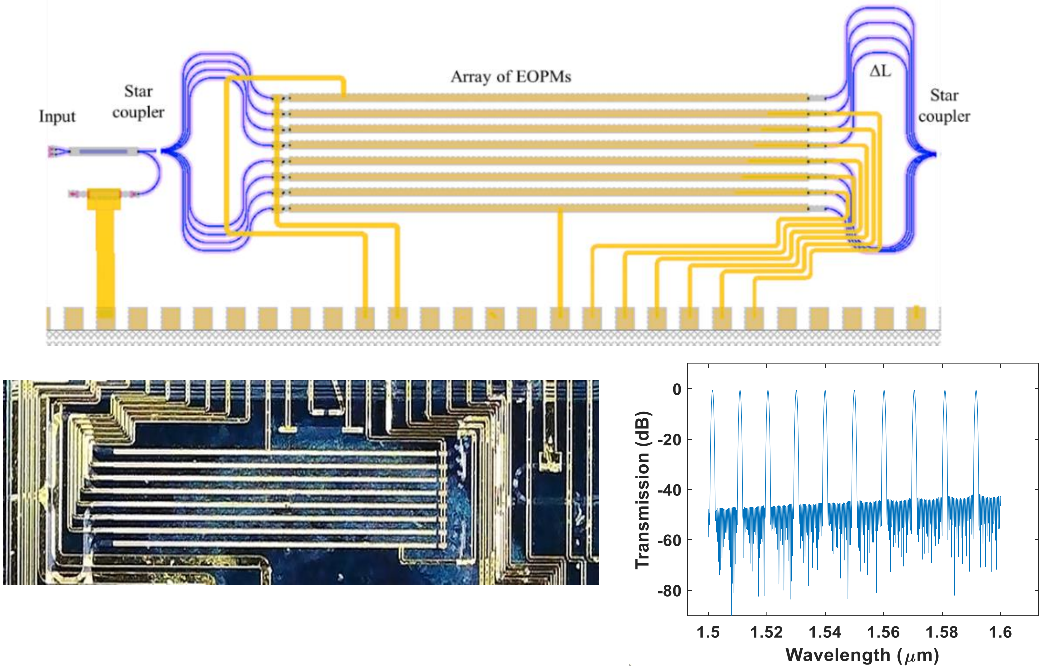

Figure 1: (a) GDS design of the realized filter. (b): Microscopic picture of realized chip. (c): Stimulated profile of filter structure resulting in a wavelength dependent sinc function

PIC design and filter mechanism

Papers The GDS of the designed filter consists of 8 MZI arms as shown in Figure 1a. A star coupler of 1:8 configuration is used to couple and split the light. The pitch and waveguide width of the star coupler is chosen such that we have equal power distribution on the arms. Each arm has individual phase control through an EOPM with length of 2400 µm. By design the EOPMs can have a phase shift of 12 to 15 degree/ V.mm. So the theoretical V_{π} value is 6.24 V.

The geometric length mismatch results in the sinc shape of the filter, and it also determines the free spectral range (FSR) of the filter. The designed FSR is 10 nm. The filter is tuned by varying the voltages on the EOPMs within the range of 0 to $V_{2\pi}$. The goal is to get constructive interference between the light from each arm for the target wavelength (λ_{target}). Figure 1b shows the realized chip on the InP platform developed by Smart Photonics on a multi project wafer (MPW) run.

To tune the filter, different kinds of waveforms can be implemented for the voltage signals. A sawtooth or a sine waveform can be a viable option. The theory and mechanism of the sawtooth tuning is described in detail in a previous work [12]. Certain challenges are foreseen in tuning with preset waveforms. First of all, contrary to theory, the initial condition of the relative voltages on the filter arms are unknown to us. One way of finding the initial condition can be using a genetic algorithm [13]. Moreover, the number of combinations required for trial to find out the optimum combination for a target wavelength is too large. Even for 10 voltage steps, the number of combinations to try becomes 10^8. In this paper we present a more time- efficient approach of using an optimization algorithm rather than using waveforms. The measurement setup and the algorithm is discussed in detail in the further sections.

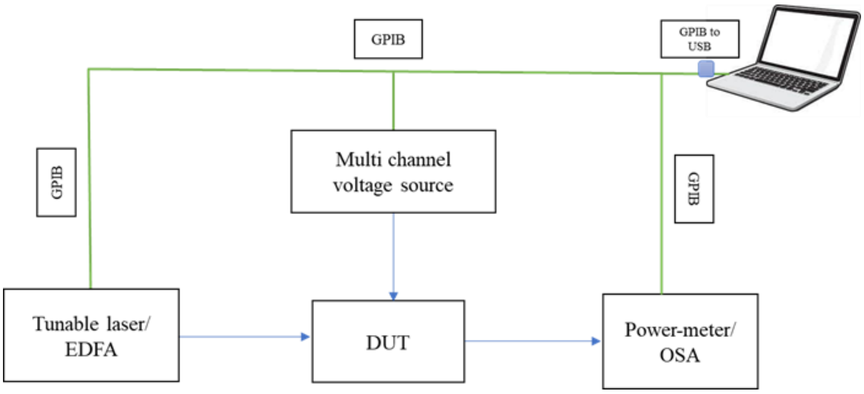

Figure 2 Experimental setup for filter measurement.

Experimental setup and optimization loop

The measurement setup is illustrated in Figure 2. The setup is connected in two ways: a tunable laser source (TLS) coupled with power meter (PM) and erbium doped fiber amplifier (EDFA) coupled with optical spectrum analyzer (OSA). The EDFA works as an input broadband source and OSA to collect the optical spectrum. A multichannel voltage source is used to apply the voltages. The voltage source, PM and OSA are connected to the computer via a general-purpose interface bus (GPIB) to sweep the different voltage conditions automatically and for recording the data in an automated way. To achieve a tuning of 10 nm, the range 1548 to 1558 nm has been split into 10 steps where, at first, the TLS is kept fixed at $\lambda_{target-1}$ and the output is recorded through the PM. Given this configuration, we ran the optimization algorithm, which outputs an array of voltages that gives maximum transmission for that target wavelength. After this, the full spectrum is collected, and the TLS takes a step forward in wavelength to $\lambda_{target-2}$ and so on.

The optimization algorithm chosen for this specific task is the Nelder-Mead stochastic search. It is based on the convergence of the vertices of a simplex of N+1 dimensions with respect to the degrees of freedom of the search domain (8 in our case) into a single point. Given a starting seed, the 9-dimensions polyhedron will shrink towards degeneration by following iterative evaluations of the target function (optical power in our case) in each vertex. At each step, all vertices but the one which has the best target function value will be then pushed in that direction.

Results and discussion

In this section we present the first results of filter tuning. Figures 3a and b illustrates the tuning of the filter for a 9 nm range, with coarse steps of 1 nm. The contour plot in Figure 3a shows the 10 nm FSR of the filter. The optimizer is implemented for tuning the wavelength range of 1548-1557 nm. After obtaining the optimized voltages, we recorded the spectra to retain the filter shape.

Figure 3b shows the peak wavelengths obtained during tuning. We find that the optimizer works with a maximum error of 0.63 nm from the target wavelength. This is attributed to the error of calibration of the optimizer. The reliability of the filter is checked with two trials, and maximum error between two trials is 0.12 nm.

In Figure 4a we show the tuning waveforms that are retrieved from the search algorithm. The range of voltage is limited by the multi-channel voltage source that has a range of ±10V. In future measurements, we will implement a range that can cover the $V_{2\pi}$ range.

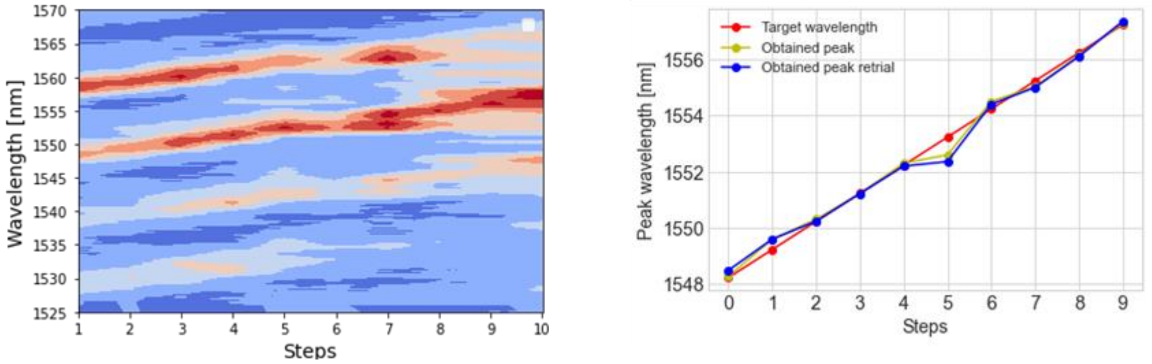

Figure 3: (a) Contour plot showing tuning of filter with 10 steps with each step of 1 nm. (b) Peak wavelength with target wavelength in red and retrials in green and blue

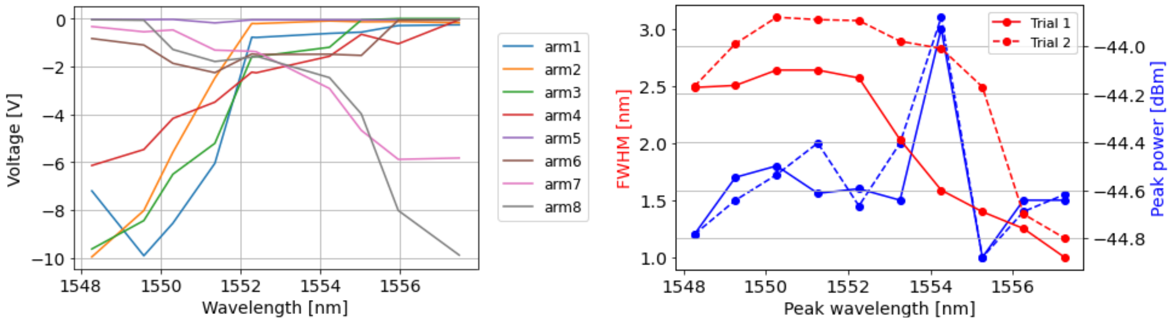

Figure 4: (a) The phases of 8 arms with tuning. (b) Evolution of filter parameters FWHM and peak power with tuning. The dashed and solid lines correspond to two trials of measurements respectively.

In Figure 4b, the evolution of FWHM and peak power is shown with tuning in wavelength. It is seen that the filter shape changes through the measurement, the FWHM varying from designed value of 1 nm, increasing up to 3.5 nm. This can be because of the limitation of the optimizer, as it optimizes on the peak power and does not yet take into account the shape of the filter. The peak power also varies, but that can be an effect of the setup or misalignment of fibers. These results can be further improved with increasing the number of steps to omit the outliers and improving the optimizer by scattering the starting seed.

Conclusion

The first results of an 8 arm tunable filter with a stochastic search based optimization algorithm is presented. The filter is tuned for a 9 nm range, with results shown for different parameters such as peak wavelength, FWHM and peak power. The algorithm can be further improved by feeding the spectra results to converge to vertices that have the best peak power as well as side-mode-to-main-mode-ratio (SMTR) and FWHM. Further work involves improving the search algorithm and implementing it in measuring tunable lasers that contain this kind of filter.

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