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Citation for published version (APA):

Docter, B., Pozo, J., Ermakov, I. V., Leijtens, X. J. M., Karouta, F., Beri, S., Danckaert, J., & Smit, M. K. (2010). Integrated filtered-feedback tunable laser with enhanced control of feedback phase. In J. Pozo, M. Mortensen, P. Urbach, X. Leijtens, & M. Yousefi (Eds.), *Proceedings of the 15th Annual Symposium of the IEEE Photonics Benelux Chapter, 18-19 November 2010, Delft, The Netherlands* (pp. 285-288). TNO.

Document status and date:

Published: 01/01/2010

Document Version:

Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
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Integrated Filtered-Feedback Tunable Laser with Enhanced Control of Feedback Phase

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Recently we presented a novel discretely tunable laser that consists of a Fabry-Perot laser which was forced to operate in single-mode condition by applying on-chip filtered feedback. The laser switches extremely fast (3 ns) and requires simple on/off control currents to switch the wavelength. In these first devices it was not possible to control the phase of the feedback light independently from the feedback intensity. In was solved by adding an extra electrode allowing us to control the phase separately. In this paper we present the new device and study the effect of the control of the feedback phase in order to improve the performance of the original tunable laser concept.

Introduction

Tunable lasers are key components in today's optical communication systems. They offer advantages in flexibility over fixed-wavelength lasers and recently there have been several advances in using a tunable laser as a switching component [1]. Further development of such switching systems requires fast and stable tunable laser sources.

Recently we reported the invention, fabrication, modeling and initial characterization of a new Integrated Filtered-Feedback Tunable Laser (IFF-TL) [2]. This device was designed in order to reduce the temperature-induced frequency drifts caused by the electronic control currents by placing the switching electrodes outside the main laser cavity. This simplifies the wavelength control and allows very fast switching speeds. For the first generation of devices, we found that the switching speed can be as low as 3 ns. We also found that the control currents have a wide operating regime, allowing a simplification of the control currents and eventually a reduction of the calibration and testing times of these devices [3].

In this paper we present an improved laser design that allows us to separately control the feedback amplitude and phase. This allows us to experimentally show that the device is very tolerant to the exact amplitude and phase of the feedback light.

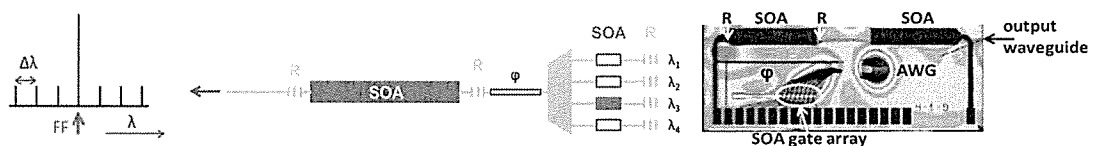


Fig. 1: Schematic diagram of the new Integrated Filtered-Feedback Tunable Laser. The inset on the left shows the possible laser modes and the filtered feedback (FF) applied to the central wavelength. The picture on the right shows a microscope image of the fabricated device. This particular device also contains a booster SOA in the output waveguide.

2. Device details and switching model

A schematic picture of the novel IFF-TL is shown in fig 1. A Fabry-Perot (FP) laser is formed by a Semiconductor Optical Amplifier (SOA) and two deeply etched broadband DBR mirrors (R). The laser cavity length ($L_{\text{cav}} = 822 \mu\text{m}$) is chosen such that the mode spacing equals 50 GHz (0.4 nm) - the channel spacing in the standard ITU-grid.

The FP laser is coupled to an AWG filter, with a 400 GHz (3.2 nm) channel spacing, that splits the light of the FP laser in several waveguide branches. Each branch contains a 30- μm -long SOA that works as an optical gate. When the SOA is not biased, it will absorb the light, but when put in forward bias ($\sim 5 \text{ mA}$), the light will be transmitted. The light is then reflected by another DBR mirror and fed back through the AWG into the FP laser. The feedback light causes injection-locking of the laser mode with the largest feedback strength, forcing single mode operation. The laser can be switched to a different wavelength by changing the current in the small SOA gates in the feedback section. Because these SOAs are not part of the main laser cavity, local temperature changes due to changed control currents do not affect the lasing wavelength.

The operating principle of the multimode IFF-TL was simulated by numerically integrating the set of delay differential equations for the competing electric fields of each mode and a common carrier number. The feedback is added in the model according to Lang-Kobayashi [4]. The frequency selective optical feedback is taken into account by adding in the system an auxiliary variable describing the filtered feedback field [5]. For more details of the model see [2]. The model predicts a switching time down to 0.5 ns, depending on the feedback strength and phase. The feedback strength is determined by a lot of factors including DBR reflectivity, loss in the AWG, gain/absorption in the SOA gates and the phase of the feedback signal. A typical model result is shown in fig. 2.

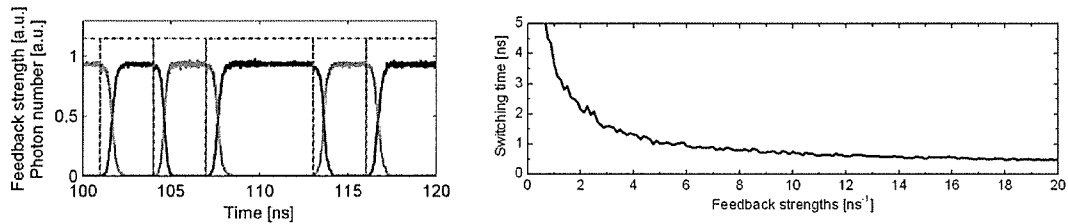


Fig. 2: Simulated switching between two modes (left). The solid lines show the optical power in both modes, the dashed lines show the difference in feedback strength. The influence of feedback strength on switching speed is shown in the plot on the right.

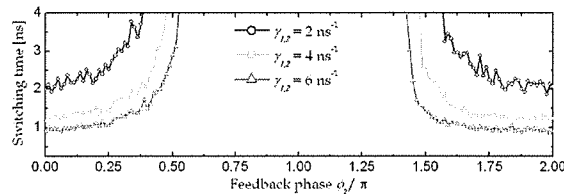


Fig. 3: Calculated switching speed as a function of feedback strength and phase of the feedback light.

A more detailed view on the switching behavior as a function of feedback phase is given in fig. 3. This figure shows that the device switches very fast for quite a large range of phase values around $\phi=0$. For phase values around $\phi=\pi$, the feedback light actually suppresses laser operation in that specific wavelength. The figure shows that as long as

the feedback phase is somewhere around $\varphi=0$ the device will switch fast, and accurate phase matching of the feedback light is not required.

To confirm this predicted behavior, we included a phase control section in the design. This phase section is placed in between the main laser cavity and the AWG filter. It can therefore be used for all the different feedback wavelengths. It is operated by applying a reverse bias voltage between -15 and 0 V.

3. Characterization

The fabricated devices have a threshold current of 15 mA at 20 °C. For the characterization of the tunability, the device was forward biased at 30 mA. Unlike the device shown on the right of fig. 1, the device used for the switching measurements did not contain a booster amplifier. An output power of 50 μ W has been collected using a lensed fiber. The reason for the low power output is the bad matching of the light from the semiconductor waveguide to the lensed fiber. The static operation of the device is shown in fig. 4 (left). Each color represents the optical spectrum of the device when the various gates are operated in forward bias.

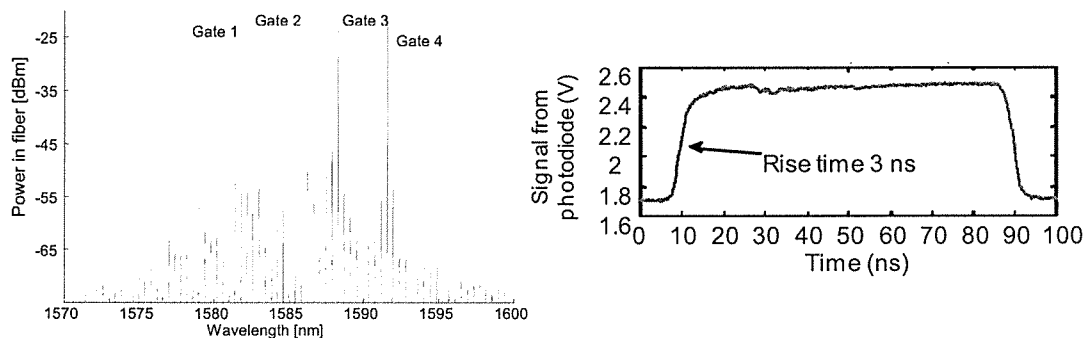


Fig. 4: Optical spectra of the IFF-TL (left). The right figure shows the result of the characterization of the switching time, 3ns.

In order to characterize the switching speed, a square signal was applied to one of the SOA gates. At the output of the laser a tunable filter was used to filter the wavelength of interest. The output of the filter is connected to a 10-GHz photodiode and electrical amplifier. The resulting RF signal is studied in a digital oscilloscope. In fig. 4 (right) the result is plotted, showing a transition time of 3 ns for both the rise and decay time. Compared to the simulation results shown in fig. 2, this corresponds to a relatively low feedback strength. We believe this is caused by high losses in the DBR mirrors or by losses in the AWG filter.

To study the device behaviour with respect to the feedback phase we first characterized the phase control section separately. We used a straight waveguide containing a phase control section of 1 mm length and two cleaved facets forming a Fabry-Perot resonator. A tunable laser source ($\lambda=1570$ nm) was used to launch light through the resonator and the light was collected with a photodetector, as shown in fig. 5 (left). By changing the reverse bias applied on the phase control section, we can move from one resonance state to the next, as shown in fig. 5 (right). The bias voltage required to do so corresponds to a phase shift of π rad. For the current device the phase shifting efficiency is $V_{\pi}=8.7$ V/mm.

To further characterize the laser behaviour due to the feedback phase, we operated the laser with one of the gates in forward bias and scanned the reverse bias applied to the

phase control section between -15 and 0 V. The graph in fig. 6 (left) shows the color-coded spectra. We can clearly see a periodic behavior with areas where the device is working in single mode operation (from $V_{\text{bias}}=-12.5\text{V}$ to -10.5V and from $V_{\text{bias}}=-2.5\text{V}$ to 0V). From this result we can extract a phase shifter efficiency of $V_{\text{pi}}=10.2\text{ V/mm}$. The difference in phase shifting efficiency can be attributed to fabrication variations.

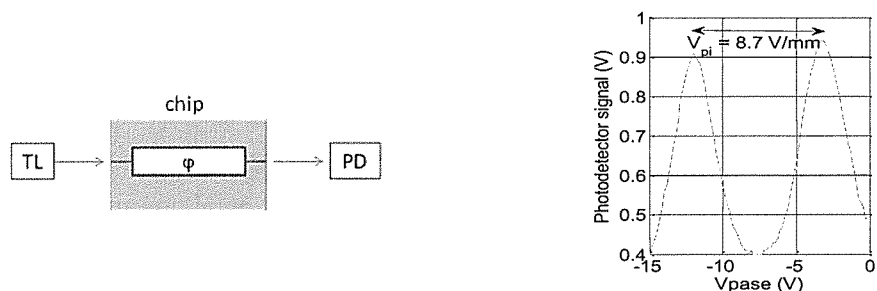


Fig. 5: Measurement setup (left) and result of phase shifter characterization (right).

In fig. 6 (right), the optical spectrum operating the device in phase for single mode operation, -12V (top), and destructive phase, -6.7V (bottom) is plotted. Here it is observed that varying the voltage of the phase controller a major improvement of the SMSR of up to 40dB can be obtained.

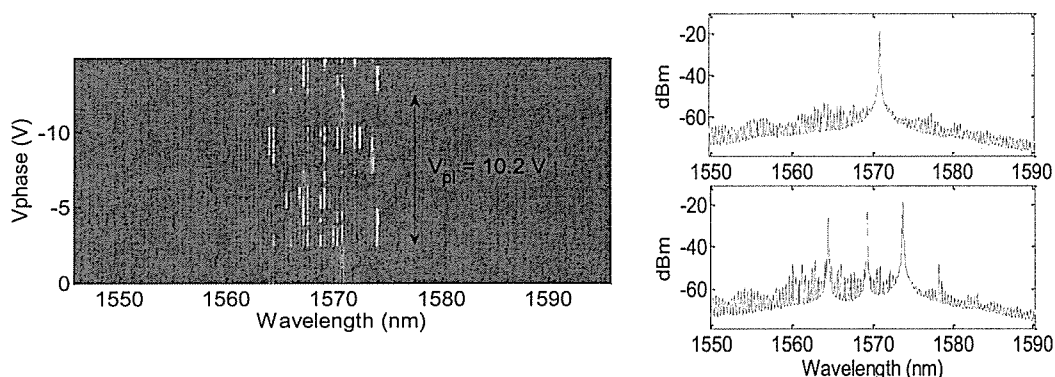


Fig. 6: Color coded lasing spectra as a function of reverse bias voltage (left). Two optical spectra, when operated in constructive (-12V) and destructive (-6.7V) phase are shown on the right.

4. Conclusions

The new concept of the IFF-TL combines high switching speeds with simple wavelength control. Theory predicts that fast switching can be achieved using tolerant control signals. In this paper we present the first experimental results confirming single mode operation over a large range of feedback phase values. This allows a simplification of the electronic tuning tables required to operate these types of devices. Apart from potential cost saving on required electronics, this can also result in less calibration and testing time of these products.

5. References

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