Fast Wavelength Thermal Tuning of DFB Lasers for Ultra Dense WDM-PONs

Santiago Tabares, Victor Polo, and Josep Prat, *Member, IEEE*

***Abstract*—Thermal tunability for distributed feedback lasers is generally done at slow tuning speed. We study laser current boosting and implement a pre-equalization stage for short wavelength jump, improving the tuning time to the half. A wider jump is also done under a more practical context.**

***Index Terms*—Electrothermal effects, Equalizers, Laser thermal factors, Laser tuning, Optics, Optical fiber lasers, Thermoelectric devices, Thermal variables control.**

I. Introduction

Ultra-dense wavelength division multiplexing passive optical networks (UDWDM-PON) with low-cost coherent transceivers potentially offer multi-user connectivity with high spectral efficiency, as compared to conventional passive optical networks (PONs). Under this architecture, the optical network unit (ONU) must provide wavelength allocation of the light source with high accuracy and speed. For cost compatibility with conventional PONs, distributed feedback (DFB) lasers can also be used in coherent PONs, then as narrowly tunable directly modulated lasers. By using a dynamic wavelength allocation algorithm, 256 DFB ONUs can be distributed in C-band in a Fiber-to-the-Home (FTTH) access PON, with 6.25 GHz channel spacing [1]. DFB wavelength tuning can be performed by varying the laser current and with a thermoelectric cooler (TEC). Varying the laser current changes both its wavelength operating point and its optical power, and tuning is constrained to a limited range of currents. Thermal tuning enables a wider range of tuning but thermal dynamics are slow taking tenths of seconds to allocate the laser wavelength. A previous work demonstrated fast wavelength switching [2] by laser current injection, but changed the bias conditions and distant channels might require low currents near to threshold, diminishing the system performance. An initial fast tuning with laser current returning to its bias value can be used to avoid this issue [3], using the temperature as the final tuning signal; nevertheless, there is still a Joule Effect caused by the laser current variation, which causes a wavelength drift for some seconds while the system reaches its new equilibrium. In this context, we propose and develop a novel wavelength tuning made by simultaneous pre-equalization of both temperature and current injection, considering the mixed problems described before, over conventional low-cost DFB laser modules with TEC control. We show the obtained high improvement in tuning time and accuracy of this novel method.

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II. Method

Commercial DFB lasers for WDM are commonly assembled inside a transistor-outline-can (TO-CAN) or butterfly package including a TEC and a negative temperature coefficient (NTC) resistor to measure the TEC cold layer temperature. An external controller to TEC input improves time response and stability [4-6]. In our case, a proportional-integral (PI) feedback closed-loop structure is implemented, as shown in Fig. 1. P and I parameters were chosen such that thermal response is 3 to 5 times faster than without TEC controller without overshoot. We thus have at our disposal a 2x2 system with the laser current and closed-loop temperature-set as input signals, and the optical power and wavelength as outputs. We then add a pre-equalization stage to these inputs to control the laser in a coordinated way.

We model the wavelength dependence as the sum of transfer functions in the Laplace s-space of thermal and electric dynamics between the elements of Fig. 1. Laser power varies mostly linearly with the current above the threshold, and also has a small negative dependence on the temperature. These equations can be put into matrix form as follows

$$\begin{bmatrix} P(s) \\ \lambda(s) \end{bmatrix} = \begin{bmatrix} k_{ef} & k_{TP} \\ H_{\lambda I}(s) & H_{\lambda T}(s) \end{bmatrix} \begin{bmatrix} I_{laser}(s) \\ T_{set}(s) \end{bmatrix} \qquad (1)$$

Here, P is the output power, λ is the output wavelength, I_{laser} is the laser current, T_{set} is the temperature signal to PI closed-loop, k_{ef} is the efficiency constant of the laser, k_{TP} is the negative temperature to power dependence coefficient, and $H_{\lambda I}$ and $H_{\lambda T}$ are the single-valued transfer functions from input signals to wavelength, containing the chirp, Peltier and Joule effects. These transfer functions are determined experimentally [7].

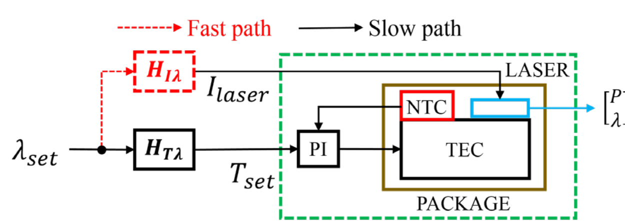

Fig. 1. Pre-equalization stage black diagram and laser package with PI feedback closed-loop

The equalization consists of varying the signals around a reference (I_{BIAS} for current and T_0 for temperature) as

$$\begin{bmatrix} I_{laser}(s) \\ T_{set}(s) \end{bmatrix} = \begin{bmatrix} H_{I\lambda}(s) \\ H_{T\lambda}(s) \end{bmatrix} \lambda_{set}(s) + \begin{bmatrix} I_{BIAS} \\ T_0 \end{bmatrix} \qquad (2)$$

These equalizers have to be made satisfying the following conditions: 1) The output wavelength λ must be ideally equal to the input tuning wavelength-set variable λ_{set} and 2) The laser injection current must provide the initial tuning in order to compensate the slow thermal dynamics and not to saturate the TEC. The first requirement imposes (3) to design $H_{I\lambda}$ (wavelength tuning to laser current equalizer) and $H_{T\lambda}$ (wavelength tuning to temperature input equalizer):

$$\begin{bmatrix} H_{\lambda I}(s) & H_{\lambda T}(s) \end{bmatrix} \begin{bmatrix} H_{I\lambda}(s) \\ H_{T\lambda}(s) \end{bmatrix} = 1 \qquad (3)$$

The second requirement directly relates $H_{I\lambda}$ with the system's thermal transfer function $H_{\lambda T}$. Since it must compensate the slow thermal behavior with a fast response, it has to be the complementary of $H_{\lambda T}$ (multiplied by a proportionality constant k with units $A^\circ C/_{nm^2}$), as shown in (4):

$$H_{I\lambda}(s) = k(1 - H_{\lambda T}(s)) \qquad (4)$$

$H_{I\lambda}$ equalizer results to be a first-order high-pass filter (HPF) [2] whereas $H_{T\lambda}$ is a second-order equalizer. Nevertheless, $H_{T\lambda}$ can be decomposed as a series HPF with parallel low-pass filter (LPF) and HPF, each one as a first-order filter, which enables perfect superposition with low-cost analog devices.

Fig. 1 represents the block diagram of the equalization. We use both the temperature to tune the wavelength in spite of its slow dynamics. For this reason, we use the laser current to perform an initial fast tuning transient while the temperature comes on, to finally return to its bias value. Then we can make a distinction between electrical fast branch (dashed lines) and thermal slow branch (solid lines).

III. Experimental Set-up

Two experiments are made: the first one performs a narrow instantaneous tuning and shows how the system behaves when we apply the equalizers subsequently. Then, we perform a greater wavelength jump in a more realistic scenario.

To acquire the required values, the setup shown in Fig. 2 was used. The equalization of signals is done analytically and also using Simulink software, and they are sent to an arbitrary waveform generator (AWG), which introduces them as the inputs of the circuit. I_{laser} goes directly to laser chip, whereas T_{set} first passes through the PI feedback closed loop. Some ADC are used to monitor the laser current, TEC input current and NTC voltage, so we know the laser temperature evolution. The optical output of the laser is beaten with the signal of an external cavity laser (ECL) using a 50/50 coupler. One of the signals of the coupler is driven to a power sensor whereas the other one is heterodyned, as shown in Fig. 2. Signals are acquired at 200 milliseconds sampling rate. The detected

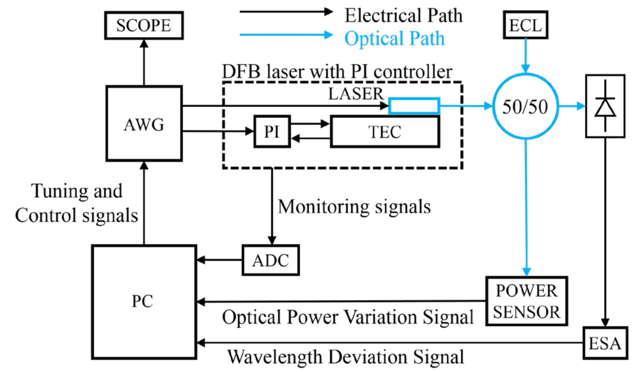

Fig. 2. Experimental setup

wavelength and power are sent to computer for their subsequent analysis using an electric spectrum analyzer (ESA).

IV. Results

For the first experiment, the environmental temperature was around 25 °C, the laser current was set to 58 mA and the TEC input current to 18 mA which sets its cold layer to 30 °C, assumed as the laser temperature. Under these conditions, the laser wavelength is 1552.653 nm at 4.4 dBm optical power. To tune 0.05 nm away of the current position, the TEC input current is set to 15 mA, increasing 0.52 ºC the temperature in steady-state.

To test the performance of each equalizer three tests are done: 1) Thermal tuning introducing a voltage step to the closed loop (no equalizers), 2) Current boosted thermal tuning (with equalizer $H_{I\lambda}$ only) and 3) Current boosted/held by temperature thermal tuning ($H_{I\lambda}$ and $H_{T\lambda}$ working together). Each one starts at 1552.653 nm and goes to 1552.603 nm (6.25 GHz difference in frequency domain).

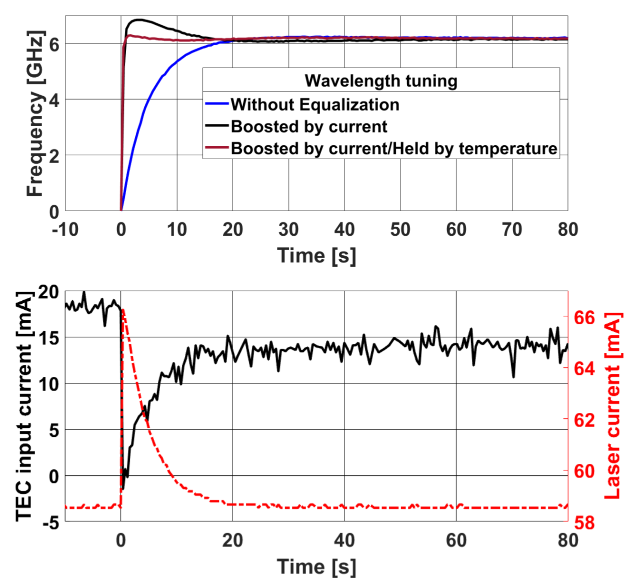

Fig. 3. (a) Frequency change for each case, (b) TEC input current and laser current with $\boldsymbol{H_{I\lambda}}$ and $\boldsymbol{H_{T\lambda}}$ working together.

Fig. 3a shows the measured optical frequency variation in time, with respect to 1552.653 nm (0 Hz variation) in the 3 cases: 1) Using only the temperature to tune the laser, the wavelength lasts around 20 seconds to reach the 95% of the settling point (blue trace); 2) If we tune simultaneously with current while the laser temperature reaches its final value, the switching is instantaneous (black trace), but now a 593 MHz drift appears due to the Joule effect coming from the change of laser current and its subsequent fast heating; 3) To fix it, the square step applied to temperature input is filtered by $H_{T\lambda}$ so the TEC deals with this thermal inertia (red trace), reducing the overshoot to 40 MHz, plus a slower oscillation of 144 MHz only to the opposite side, disappearing after some seconds. With these equalizers, the wavelength jump is done instantaneously (less than the 200 milliseconds sampling time) and precise, below 2% error. This drift falls within the frequency compensation range of the coherent receivers and does not affect the transmission performance [8].

The applied currents to TEC and laser are plotted in Fig. 3b. As expected, the laser current variation over the reference has the shape of the output of a first-order HPF, whose maximum is 66 mA (around 8 mA increase over reference). The TEC input current follows a high-pass shape too, due to the PI feedback closed-loop structure, varying over its 18 mA reference and settling to 15 mA. The advantage of using thermal tuning instead of laser current injection is that optical power remains almost constant due to its low thermal dependence. However, there is still power variation at the edges because of the change of laser current. Keeping this variation less than 30 mA over 60 mA reference, the power is kept inside 4 dB variation, rapidly returning to the nominal bias. This condition establishes the tuning limit: to tune up/down 3 channels at once (18.75 GHz) requires an absolute deviation of 24 mA over reference of the laser injection current. To switch more than 3 channels would increase/reduce the optical power outside the allowed margins. However, this restriction corresponds to the instantaneous wavelength jump. Increasing up the switching time (applying a ramp instead of a step) reduces the maximum laser current deviation, enabling us to perform a wider wavelength jump, as follows.

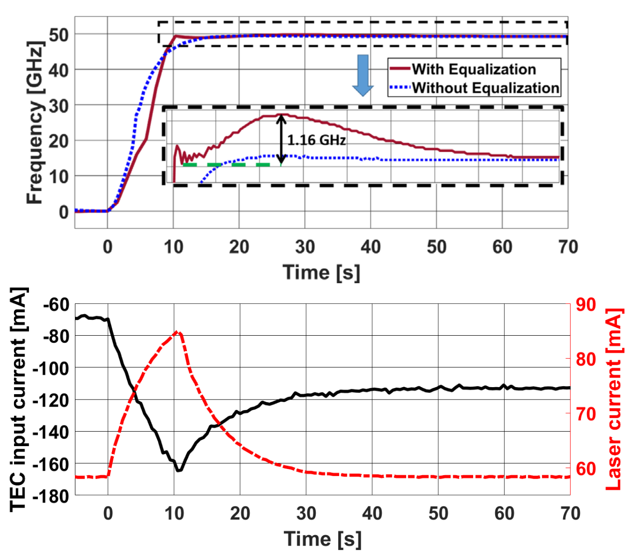

Fig. 4. (a) 50 GHz thermal tuning zoomed in, (b) TEC input current and laser current for 50 GHz wavelength jump.

The second experiment aims at a wider jump, of 50 GHz (8 channels). As before, the ambient temperature is set to the average indoor temperature (25 ºC) and the TEC cold layer is set to 30°C. Under these conditions the laser is thermal tuned around 100 GHz away of its starting point, setting the TEC at -72 mA, increasing 15ºC over the initial 30 ºC. Because $H_{I\lambda}$ is by its design a HPF, a ramp signal of 10 seconds is applied instead of a simple step, thus keeping the laser current variation less than 30 mA over the reference. Because of the TEC non-linearity [5], the filters parameters of equalizers are slightly modified (less than 10%) to achieve a good performance under different conditions. All the equipment used in the first experiment is used again, but the sampling time is increased to 500 milliseconds due to a greater ESA span.

In this case, the initial wavelength is around 1551.85 nm (0 Hz variation). Fig. 4a shows the wavelength behavior (optical frequency). As we can observe, its shape follows accurately a ramp signal, which is the input of the equalizers. Zooming in the figure we can observe the settling point (final value) and an initial deviation of 360 MHz followed by the maximum deviation (840 MHz), whose sum is around 1.2 GHz oscillations, which corresponds to 1.7% overshoot. The TEC input current and the laser current are plotted again. In Fig. 4b we can see how laser current and TEC current work together to reduce the tuning time from 20 seconds to 10 seconds. Similar results are obtained with other conventional DFB lasers.

V. Conclusions

In this paper, we have demonstrated fast wavelength thermal tuning of DFB lasers for a udWDM-PON scenario . In the 6.25 GHz jump experiment, the tuning time was reduced from 20 seconds to less than 200 milliseconds with the laser current boost, with +/-90 MHz (instead of 600 MHz) transient that disappears after few seconds, also the power. To achieve a wider jump of 50 GHz, the tuning signal is a ramp signal of about ten seconds rather than a Heaviside step to avoid stressing the laser and TEC currents, and the parameters of equalization stage are adjusted. The wavelength follows this ramp signal and performs the 50 GHz tuning within 840 MHz overshoot before it settles in its target position in only half the time with the proposed equalizers.

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