Athermal Colorless C-Band Optical Transmitter System for Passive Optical Networks

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***Abstract*—This paper reports an uncooled transmitter system using a digital super-mode (DS) distributed Bragg reflector (DBR) tunable laser, which is able to act as an athermal, wavelength agnostic transmitter suitable for wavelength division multiplexed (WDM) passive optical network (PON) applications. An open-loop laser current control algorithm is designed to compensate autonomously for wavelength drift, thus allowing constant operating wavelength to be achieved regardless of ambient temperature. An improved wavelength accuracy of ±3 GHz is achieved when using low bandwidth feedback from the central office using information from a centralized shared wavelength locker. The entire laser start-up, channel selection and subsequent wavelength control is autonomous and has been implemented on micro-controllers and field programmable gate arrays. We demonstrate a three channel WDM-PON system comprising an uncooled packaged DS-DBR laser in the presence of two neighboring interfering channels. Error free transmission over 40 km single mode fiber of 10 Gb/s externally modulated NRZ data, is achieved for each of 48 C-band channels on the 100 GHz ITU grid. Successful athermal operation is demonstrated by sweeping the ambient temperature of the laser from 15 to 70 °C with a maximum wavelength deviation for any channel of no more than 0.1 nm.**

***Index Terms*—Laser tuning, optical communication, semiconductor lasers, wavelength division multiplexing.**

I. Introduction

THE demand for broadband services continues to grow and is leading to an increasing number of fiber network users [1]. To cope with this trend, various fiber-to-the-x solutions have been proposed. These include passive optical networks (PONs) which are regarded as being very promising, because of their low cost, simple maintenance and operation, and high bandwidth provision to the user [2]. FTTH / FTTP networks based on PONs, such as BPON and GPON, are already being deployed to provide broadband access [3]. Wavelength division multiplexed PON (WDM-PON) (Fig. 1) has been attracting much attention recently [4], and is widely considered to be a long term option for the next generation of high performance PONs. WDM-PONs have potential advantages of higher bandwidth and reduced latency [5]. However, for WDM-PONs to be economically feasible low cost wavelength agnostic optical components are required in each optical network unit (ONU) enabling high bandwidth up-links.

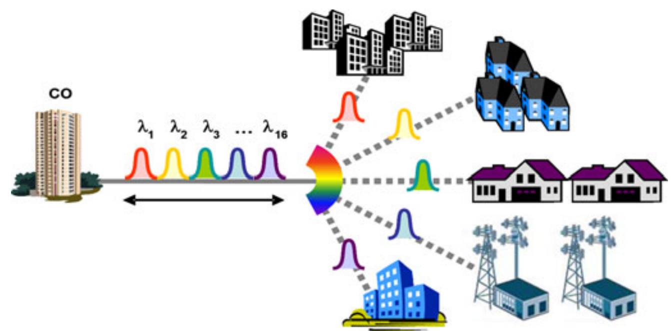

Fig. 1. Schematic diagram of WDM-PON.

A colorless optical transmitter is therefore a key component for implementation of WDM and hybrid WDM-TDM PONs, to remove the requirement for complicated and costly inventory, and network management for the service providers. Thus low cost high modulation bandwidth tunable sources have the potential to facilitate substantial CAPEX and OPEX reduction.

Various WDM-PON technologies are available for realizing a colorless customer ONU [6], [7]. For example, some have proposed the use of broadband spectral optical sources, such as super-luminescent light emitting diodes, at each customer ONU [8], [9]. In such a system, only the optical spectral component from the broadband source which can pass through the WDM MUX channel is transmitted to the central user, and the remaining power is blocked and wasted. These approaches offer cost-effective solutions but their scalability is limited because of the need to have sufficient in-band optical power to maintain an acceptable signal-to-noise ratio [10]. Reflective optical technologies, which reflect and encode the central-office downlink signal, provide a better power efficiency and signal-to-noise ratio than the previous non-seeded scheme. [11], [12] However the remote seeding requires a high power broadband seeding source from the central office and is mainly limited by the Rayleigh backscattering and reflective signals. An additional

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constraint is that schemes using modulators such as reflective semiconductor optical amplifiers (RSOAs), support only moderate line-rates up to 2.5 Gb/s. Integrated reflective EAM-SOAs offer data rates of 10 Gb/s or higher [13], but require additional control and are typically more lossy. Alternatively, RSOA based or Fabry Perot Laser based self-seeding solutions using optical reflectors at the remote node can be used to remove not only the broadband seeding source but also the signal impairment from the backscattering. Up to 10 Gb/s modulation on both systems have been recently reported. [14], [15] However, the long-reach capabilities for those systems at 10 Gb/s line-rate are still limited by the chromatic dispersion (RSOA based) and the power budget.

On the other hand, tunable lasers can offer much improved optical performance and flexibility for WDM-PONs, as these devices can adjust their wavelength precisely to the system requirement and can efficiently generate single mode optical signals. However, compared with devices used in conventional EPON and GPON systems, a much more sophisticated laser often along with post-modulation is required in the ONU. This is because the tunable laser normally requires an internal wavelength locker or an external network wavelength reference to enable operation at a known wavelength channel, and must be operated at a constant temperature, typically using a thermoelectric cooler. Furthermore, today's tunable sources require individual characterization, which is also a major barrier of reducing the CAPEX.

The DS-DBR laser, which has recently been developed by Oclaro [16], has five cavity sections including a multi-contact front grating and these features give it great control flexibility and full C-band tuneability. Therefore, it can be controlled to work as an athermal laser whose wavelength does not change with temperature [17] and may thus be operated without a thermoelectric cooler which can incur substantial cost and power consumptions. It can be envisaged that the laser could be monolithically integrated with a Mach–Zehnder modulator (MZM) as recently reported, for modulation rates of 10 Gb/s and beyond [18], suitable for deployment in high speed WDM-PON systems.

The design of these uncooled tunable lasers is somewhat challenging, with work in 2002 achieving 0.6 nm wavelength stability from 25 to 55 °C using super-structure grating DBR lasers [17], [19]. Appropriate control of the gain and phase sections in addition to the gratings achieved an improved wavelength stability of ±25 GHz (±0.2 nm in C-band) within a 60 °C range. [20] However, the tunability of these lasers was very limited until 2010 when DS-DBR lasers achieved constant wavelength operation over the whole C-band range with a wavelength stability of around ±12 GHz (±0.1 nm). [21] Nevertheless, these past designs have not removed the need for individual device characterization.

Based on these previous contributions, in this paper, we demonstrate a full WDM-PON system based upon feedback from a centralized wavelength monitoring system [22] using the DS-DBR lasers in an uncooled manner. A self-training process is also introduced in the initial calibration to avoid the need for individual laser characterization. It is successfully demonstrated that the feedback system not only helps to improve the wavelength stability but also enables plug and operation with lasers automatically aligning to the allocated ITU channel yielding simplified operation.

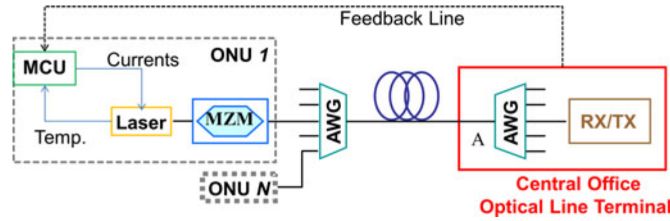

Fig. 2. Uplink diagram of WDM-PON.

II. Principle of System Operation

WDM-PONs allow high bandwidth point-to-point connections without regard to physical network topology. The wavelength of operation of each ONU is determined by its connection to a wavelength dependent splitter within the uplink path. Therefore each ONU must be able to align its operating wavelength to the channel determined by the physical topology of the fiber infrastructure. Fig. 2 shows how the system would be applied within the uplink of a WDM-PON. A micro-controller (MIC) is embedded in each ONU to apply the laser current control algorithms and monitor the laser temperature. Upon start-up the laser is controlled to sweep its emission wavelength through the spectrum by increasing the grating currents following the predefined equations which have been programmed in the MIC. The wavelength selection relies on the wavelength filtering of the arrayed-waveguide-grating (AWG), as only the correct channel will be transmitted through the AWGs in the PON system. The OLT continuously transmits the received power level back to the ONU through a feedback link. Once the ONU detects that the OLT power is above an initial threshold it halts the initial coarse wavelength sweep. A fine wavelength tuning process is then executed to ensure that the emission wavelength is aligned to maximize the received power at the OLT, followed by a self-training of the phase trajectory to ensure only one cavity mode is excited. This first stage of the initial wavelength calibration process based on the feedback signals typically takes tens of seconds. Once the laser's emission wavelength is locked successfully, it is set to autonomously maintain a constant emission wavelength by controlling the currents in different laser sections to compensate the cavity change caused by the temperature drift.

In this second stage of maintaining the wavelength, as the feedback link is not synchronized with the laser control system, the laser is initially set to operate under open loop control, which means it only responds to the local temperature changes. If we intentionally stop the feedback link, such an open loop control can lock the emission wavelength to within ±18 GHz (±0.15 nm). If however feedback information containing a wavelength error is received from the OLT, the original control is immediately augmented and the error information will be used to correct the grating currents, which helps the ONU emission wavelength to be locked within ±3 GHz (±24 pm).

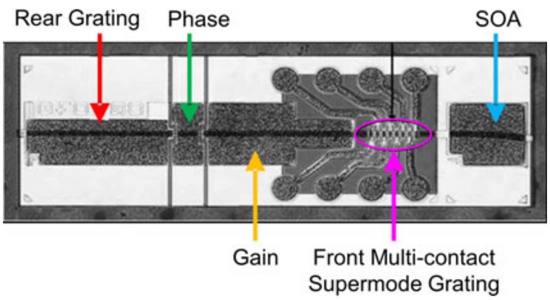

Fig. 3. Top view of a DS-DBR laser chip after [16].

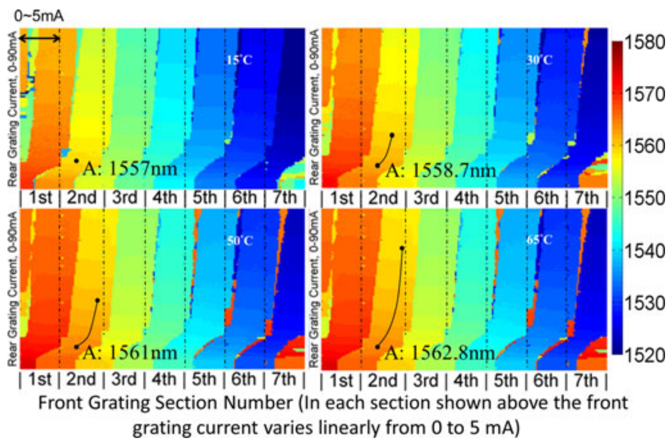

Fig. 4. Output wavelengths at different front and rear grating currents at 15, 30, 50, and 65 °C.

This paper describes the operation of the DS-DBR laser over all ITU C-band channels and over a temperature range of 15–70 °C.

III. Laser Details and Athermal Wavelength Control

A. DS-DBR Laser

Fig. 3 shows the topview of the DS-DBR laser we used. The laser consists of gain, phase, rear grating and multiple front grating sections [16]. Sub-band selection is made by adjusting the injection current to a pair of adjacent front grating contacts. The output wavelength is tunable within a sub-band by controlling the front grating, rear grating, gain and phase currents. In combination, this laser allows a continuous wavelength tuning over a range of typically 45 nm or more. In addition, a semiconductor optical amplifier is integrated at the front end to enable output power equalization. In most system applications, the laser is operated in CW mode, and is monolithically integrated with a high speed MZM [23], for a 10 Gb/s WDM-PON uplink. Alternatively, the integrated SOA can be directly modulated with NRZ data for slower speed applications removing the need for the MZ modulator.

B. Wavelength Drift and Tuning Methodology

Fig. 4 shows tuning maps (plots of emission wavelength versus front and rear grating currents) for the laser. These are included at four different temperatures. The front grating section numbers along the *x*-axis correspond to each different supermode, and in each section the front contact current varied between 0–5 mA. It can be seen that, the laser's emission wavelength is gradually red-shifted, at a rate of 0.11 nm/°C, as the temperature increases as shown for point *A* in Fig. 4.

Constant wavelength operation however can be achieved by varying the front grating current as a function of rear grating current, as shown by the black curves. If we collect data points along the black curve in a single grating current tuning map, we can extract the relationship between the emission wavelength and the grating current combinations (as each point on the tuning maps stands for a combination of front and rear grating currents). The absolute wavelength may differ slightly from laser to laser, but the trend of wavelength variation versus the grating currents is identical for all lasers. Therefore, the relative wavelength variation can be expressed as a generic function of the grating currents, which is stored in every ONU device so that they can derive the desired grating currents from the required wavelength change.

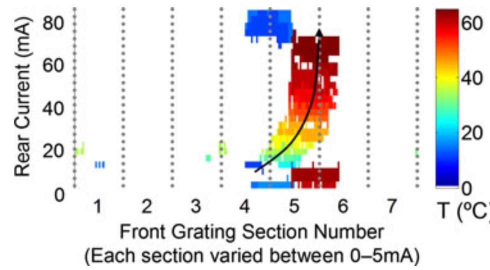

Fig. 5. The front and rear grating currents required for operation at 1537.7 nm over a 50 °C range.

C. Initial Front and Rear Current Control Over Temperature

Fig. 5 shows the rear grating current required for operation at an example wavelength (1537.7 nm) as the temperature varies from 15 to 65 °C. Wavelength stabilization is achieved by increasing the current to the front and rear gratings with temperature, as shown by the black line in Fig. 5. A generic equation has been developed which controls the current to the front and rear grating sections as a function of temperature to enable the laser to operate with minimum wavelength deviation. This front and rear grating current control achieves ±35 GHz (±0.3 nm) wavelength stability over the 15 to 70 °C temperature range. As only the grating currents are varied, undesirable cavity longitudinal mode hops occurs every 4 °C which has serious adverse consequences for PON operation and limit the wavelength stability. Therefore, active controls on gain and phase sections are also needed for a continuous single mode operation over an extended temperature range.

D. Additional Phase Current Control

Fig. 6 shows how the use of additional control of cavity length via the phase section current can improve the wavelength control. Here, the effective refractive index in the phase section decreases with increased current owing to the plasma effect.

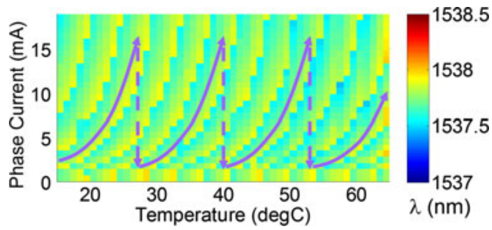

Fig. 6. Phase current plot over temperature (rear and front grating currents control is applied, while gain section current remains constant).

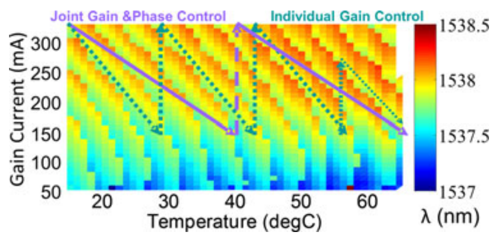

Fig. 7. Gain current plot over temperature (rear and front grating currents control is applied, while phase section current remains constant).

Thus an increase in the phase current as a function of temperature can maintain a constant laser optical cavity length since it acts in the opposite sense to thermally induced index changes. However, when the phase current reaches its maximum current limit (20 mA), it must be reset to zero, at which point a cavity longitudinal mode hop is inevitable. This method reduces the frequency of mode hopping to every 12 °C and the achieved wavelength accuracy is also improved to ±18 GHz (±0.15 nm).

E. Further Gain Section Current Control

Fig. 7 shows how the emission wavelength changes as a function of gain section current for different temperatures, where the phase section current is constant. It can be seen that the wavelength blue shifts in a periodic way with decreased gain current, which is owing to cooling and band-gap re-normalization. The green dotted line indicates the expected gain section current trace for single mode operation with varying temperature. In a similar way to the phase current control, in this method, the gain current reaches its maximum and has to be reset, causing longitudinal mode-hops at 14 °C intervals.

Therefore, to achieve the maximum temperature range of mode-hop free operation, joint control of the currents of both gain and phase sections is implemented. In this method, the variation of gain section current with temperature is modified and is shown in the purple lines in Fig. 7, in which only a single current reset is needed within the temperature range. Clearly, without any control on the phase section current, a few mode-hops will occur when the temperature varies from 15 to 70 °C. Fig. 8 shows how the emission wavelength varies with phase current at different temperatures when the gain current is tuned following the purple lines in Fig. 7.

This joint control mechanism stabilizes the optical length of the cavity over an extended temperature range of more than 26 °C, with only a single controllable current reset. This range of

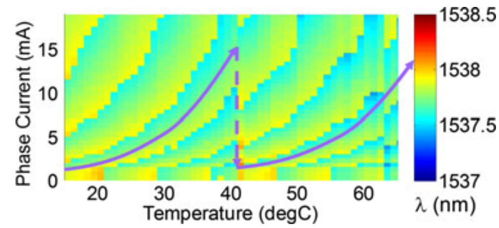

Fig. 8. Phase current plot over temperature (front and rear grating currents control is applied, and gain current is controlled as the purple lines in Fig. 7).

mode-hop free operation results from the geometry of the laser cavity itself and can only be increased if a re-designed cavity with a longer phase section is used. It should be noted that the control of gain section current results in a slight fluctuation within 3 dB in output power, which is then compensated by using the integrated SOA.

F. Switching Between Super-Modes

The emission wavelength can only be tuned in an 8–9 nm range within a single supermode, a limitation of the maximum values of grating currents which can be applied to the device. Thus, for some channels close to the edges of those wavelength ranges, they may need to switch to a neighboring supermode to maintain its constant emission wavelength. It should be noted that as there is 1–2 nm overlapping between the wavelength ranges of adjacent supermodes, the temperature where the laser needs to switch to the next supermode is different from the temperature where it has to be switched back. Therefore, there is enough hysteresis to prevent the laser from oscillating between two supermodes even though the temperature might oscillate around a switching value.

G. Self-Training Process for Individual Lasers

In this work, general relationships for the front and rear grating currents and the equations of phase and gain section currents versus the laser temperature are derived from typical tuning maps. Therefore, owing to fabrication tolerances, these relationships are slightly different from device to device. When installing a new device, these generic relations will be initially applied. However, with the help of the feedback control mechanism, any laser will nevertheless converge to the correct wavelength by sweeping the grating current. The generic trajectory for the phase current may allow the co-existence of more than one cavity mode, therefore, a self-training process is included in the wavelength calibration to optimize the phase current trajectory to ensure that only one cavity mode is selected at any temperatures.

The self-training starts by giving an offset on the original phase trajectory and increasing this offset step by step until a major power loss or a sudden large wavelength deviation is spotted, which indicates a cavity mode-hop occurs. Then the ONU starts decreasing the offset until another mode-hop is observed. These two values of the offset will be marked as the boundaries of the single mode operation region. And the phase

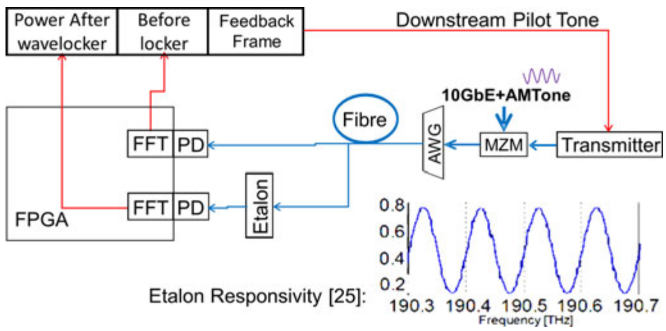

Fig. 9. Schematic diagram of the feedback system and Etalon's response [25].

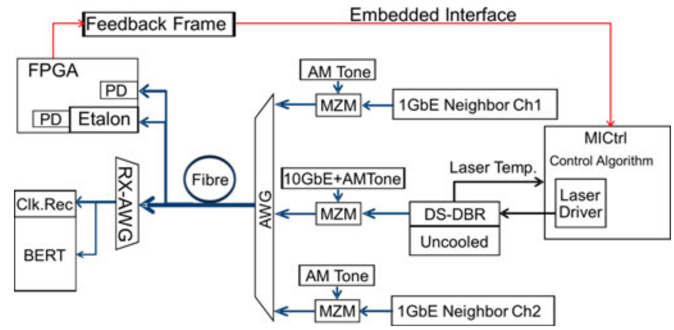

Fig. 10. Schematic diagram of the demonstration system.

current trajectory will then be offset to the middle of these two boundaries. It should be noted that during the training of the phase currents, the grating currents also need to be adjusted to maintain a constant emission wavelength.

IV. Feedback Based Closed Loop Control

After the initial sweeping of the grating currents and the self-training for phase current trajectory, every tunable source can be successfully locked with a single mode output. However, the wavelength stability is further improved by the feedback information from the centralized wavelength locker at the OLT. By appropriate implementation a single such locker can be shared between all of the up-link channels [24]. This is accomplished by applying an unique AM pilot tone (PT) to the data from each ONU (with approx. 2–10% modulation depth), as these PTs are orthogonal the intensity of each can readily be determined by performing a fast Fourier transform (FFT) on the combined signal before it is split into its constituent wavelength channels by an AWG (point A in Fig. 2). Also, to avoid extra penalty on the (high-speed) signal quality caused by the PT frequencies, they are limited to lie between 100 kHz and 1 MHz. Fig. 9 shows the schematic of the control system.

The feedback line can be implemented by a low speed signal carried by a downstream PT which is added on the designated downstream wavelength [24], and therefore the addressing of each user is avoided. This add-on feedback frame is then decoded and processed in the ONUs.

The etalon, which is used in the wavelength locker has a 100 GHz free spectral range. The ratio of the tone power before and after the etalon can be used to determine any small wavelength error present in the up-link signal. The device is operated so that it is halfway up its transfer function when the channel is aligned to the ITU grid, allowing unambiguous wavelength error information to be returned to the ONU for wavelength deviations of ± 25 GHz (± 0.2 nm). For wavelength errors greater than this the system reverts to using the tone power before the etalon.

A. Wavelength Offset Correction

Once a feedback frame is successfully received by the MIC at the ONU, it first reads the power information decoded from the feedback frame. If the power level is reasonably consistent, it will move on to down-convert the wavelength deviation from the feedback frame. Finally, the MIC inside the ONU will amend the grating currents alone the black curves shown in Fig. 4 to correct the emission wavelength according to the deviation and the instantaneous laser temperature. However, if after reading the received power, a major power drop is detected, the MIC will initiate a re-alignment of the emission wavelength in the vicinity of the desired optical channel.

B. WDM-PON System with Closed-Loop Control

To validate the proposed method, a three-channel WDM-PON system with closed-loop wavelength control as shown in Fig. 10 is built and tested [26]. At the transmitter side, the complete laser control algorithm is implemented in a MIC connecting with the laser driver chip. The channel under test uses a CW source comprising an uncooled DS-DBR laser driven by the MIC, which is modulated by a MZM with 10.3 Gbps NRZ PRBS data with a run-length of $2^{31} - 1$. Neighboring channels comprise small form-factor pluggable modules directly modulated with 1 GbE. All three channels have PTs imposed with a MZM.

At the OLT, a small proportion of the combined signal is tapped off to drive the FPGA based feedback system. The remaining signal is de-multiplexed by an AWG and the data for the center channel is tested by a BERT with a built-in clock recovery. Fig. 11 shows the BER curves for both 1 and 10 Gb/s data rate. For examine the eye closure penalty induced by the PT, BERs are measured for the B2B cases without PTs, which shows that when the modulation depth is only 2–10%, the PT only results in 0.5 dB penalty. At 1.25 Gb/s, almost penalty free operation is achieved for transmission distances up to 40 km, the 3 dB penalty at 80 km is explained by the introduction of an EDFA required to overcome the additional attenuation over this transmission distance. Similar results can be seen for 10.3 Gb/s transmission. A 1 dB penalty is seen after 20 km, with a 1.5 dB penalty after 40 km. This is worse than expected as the laser's wavelength wanders within +/− 3 GHz, which induces small phase jitters in the received signal causing the additional dispersion penalty.

Fig. 12 shows the output wavelength error from the uncooled laser over a 4 h period after the initial calibration. It can be seen that the closed-loop enables the emission wavelength to remain within ± 3 GHz of the desired channel. The small oscillations

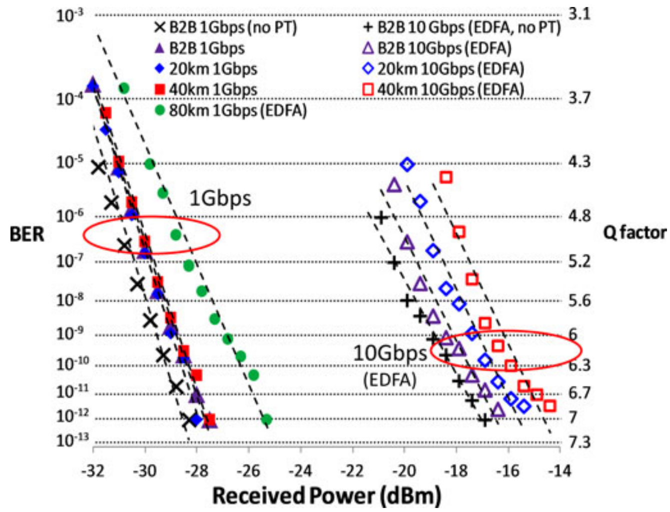

Fig. 11. BER plots for the tested system.

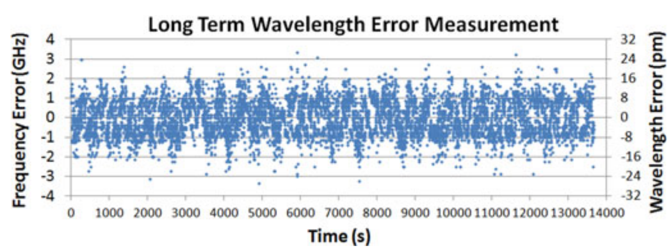

Fig. 12. Long term performance of wavelength deviation.

within the output are the result of the feedback mitigating the errors in the open loop control algorithm.

V. Full Wavelength and Temperature Characterization

In order to evaluate the performance for all ITU channels in the C-band over varied temperatures, a dynamic transmission test is carried out with similar setup to that in Fig. 10, except that, rather than left uncontrolled, this time the ambient temperature is intentionally increased from 15 to 70 °C and then decreased to 15 °C again at a rate of roughly 0.1 °C /s. In addition, in order to track the system status in real time, an optical spectrum analyzer is used to record the wavelength deviations and power levels instead of using the Etalon and FPGA board. The bit error count is recorded simultaneously for eight randomly selected channels in order to confirm error-free operation. Fig. 13 shows the wavelength stability over the entire temperature range (the nearly instantaneous controlled supermode switches are not captured in the figure). It can be seen that the maximum wavelength deviation for all channels within the given temperature range is no more than 0.1 nm. In fact, in most of the time the errors are much smaller, with standard deviations of only 0.02 nm. It should be noted that this result is tested with the feedback rate of 1 frame/s and the temperature changing rate of 0.1 °C/s. However, higher rates of temperature change can

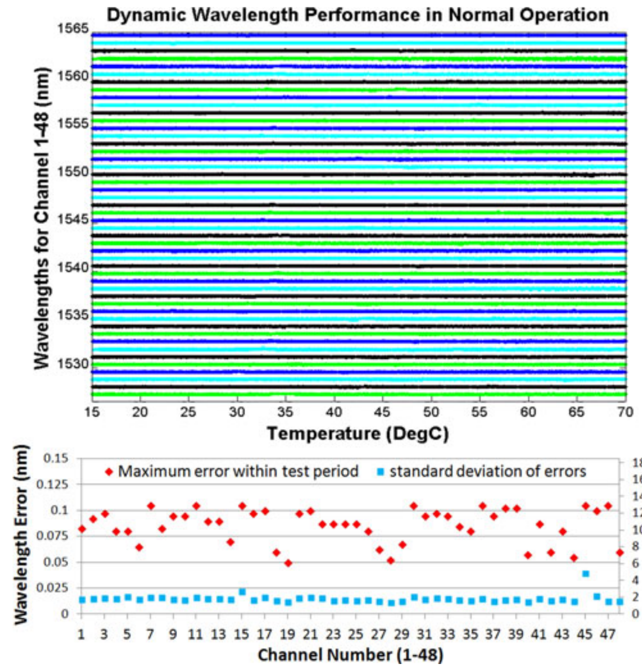

Fig. 13. Wavelength Stabilization for all 48 ITU-100 GHz channels.

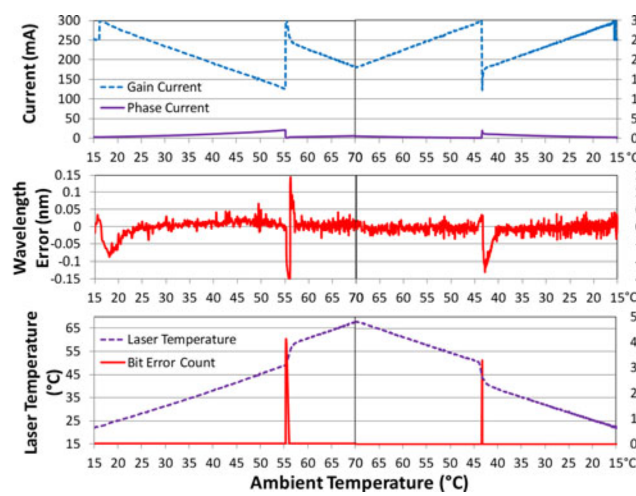

Fig. 14. System status over varied temperatures.

be accommodated with a higher feedback rate, enabling similar results to be achieved.

Fig. 14 shows, for a typical channel, how the gain and phase section currents are varied as the temperature changes and also the real-time bit error counts and wavelength error which result. It can be seen that the system can achieve error-free except for the instant when the current is reset, which leads to a burst of errors in next tens of milliseconds. It is believed that further optimization of the dynamic current control and more advanced algorithms will mitigate these error bursts.

VI. Conclusion

In this paper, a colorless transmitter with a feedback based and integrated athermal laser control unit is reported which allows temperature independent operation of 48 channels (100-GHz spacing) with fewer than two predictable mode hops across the temperature range from 15 to 70 °C. Feedback from a central wavelength locker allows wavelength stabilization in the closed-loop control system and improves wavelength control to within ±3 GHz.

To validate the application of such a transmitter system, a novel uncooled WDM-PON system is demonstrated with 10.3 Gb/s NRZ external modulation over a 40 km link. The system functions error-free with stable wavelength over a 26 °C range: Further temperature excursions can be handled by allowing a controlled laser reset, lasting only a few milliseconds.

This paper demonstrates the potential for the system as a low cost, low energy consumption and integrated tunable ONU transmitter for high performance WDM PON networks.

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