Using MZIs for Optical PSBT Transmissions: Requirements for Thermal Stabilization

Guillaume Ducournau, Olivier Latry, and Mohamed Kétata

In this paper, we discuss the quantification of Mach-Zehnder interferometer (MZI) thermal stabilization which is needed in optical phase shaped binary transmission (PSBT) links. Considering the thermo-optic and thermal expansion effects, we revisit the analytical expression for the thermal drift (GHz/°C) of the MZI center frequency (denoted here by the 'MZI spectral drift'). An MZI is then used in an experimental transmission system using the optical PSBT format. We study the effect of spectral MZI drift by using a thermally stabilized interferometer and applying a frequency shift to the optical carrier. By using the thermal drift coefficient of the MZI, we find that to ensure low bit error rate fluctuations due to the MZI drift, the thermal stabilization of the device must have an accuracy of 0.5°C.

Keywords: Optical telecommunications links, Mach-Zehnder interferometers (MZI), PSBT modulation format, thermal stabilization.

I. Introduction

Today, most optical telecommunication links use the well-known modulation format called on-off keying. Recently, new modulation formats such as differential phase shift keying (DPSK) in ultra-long haul optical communications have been considered and compared in order to increase the tolerance of the optical link to impairments such as chromatic dispersion, polarization mode dispersion (PMD) or non-linearity (Kerr Effect) [1]-[3].

Robustness to the group velocity dispersion (GVD) was first investigated with optical phase-coded duobinary signals, characterised by an optical spectrum reduced by a factor of 2. D. Penninckx and others [4] then explain that the robustness of optical phase-coded duobinary signals to the GVD effects can not be explained only by reduced optical spectrum size but by the presence for such signals of phase shifts in each 0 neighbouring a 1 ("0" and "1" represent binary data). Such a transmission format has been named a *phase shaped binary transmission* (PSBT) [4].

Standard PSBT transmitters use an electrical method to create the PSBT effect [5]: a dual drive Mach-Zehnder modulator (MZM) is driven in a push-pull configuration by a symmetrical non return to zero (NRZ) signal filtered by a 5th order Bessel filter (2.8 GHz cut-off frequency for a 10 Gbps PSBT format).

The PSBT format allows transmission beyond the dispersion limit. In other words, the maximal transmission distance (limited by the GVD effects) is increased [6]. This result justifies the interest in PSBT transmissions in reduced cost long haul (LH) applications, because the dispersion compensation scheme is limited and cheaper. Moreover, the PSBT optical format has a reduced spectrum, thus providing an OC-768 (40 Gbps) transmission on a 50 GHz ITU grid, leading to

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doubled spectral efficiency, as does the differential quadrature phase shift keying (DQPSK) modulation format [7]. Last, the reduced size of the PSBT spectrum allows the mixing of OC-192 channels and OC-768 channels on the same link, already deployed for OC-192 applications.

Recently, a new method for creating a PSBT format has been proposed in [8]. This new all-optical encoding method uses Mach-Zehnder interferometer (MZI) structures, as in DPSK demodulators. In this all-optical method, a DSPK signal is first generated and then filtered by an MZI optical filter to obtain the all-optical PSBT format (Fig. 3).

The difference is that for PSBT encoding, the MZI differential delay is not equal to the bit duration as in DPSK demodulation devices, but to a bit-time period ratio. As the time delay of the MZI is not equal to the bit-time period (denoted by T_b in the following), residual phase shifts remain in the partially demodulated DPSK signal, thus creating an all-optical PSBT signal. Optical PSBT signal generation was first reported last year in [8] showing better tolerance to GVD degradation compared to conventional NRZ amplitude schemes.

As optical PSBT signal generation uses MZI structures (temperature-dependent components), temperature can be expected to play an important role in the quality of the encoding operation at the transmitter. The MZI thermal dependence was already investigated in [9] for the realization of stabilized devices. We propose here to revisit the problem of thermal behaviour for MZIs, and our new contribution will be the determination of the thermal accuracy required for all optical PSBT format encoding.

In this paper, we first revisit the thermal behaviour of MZI structures in order to quantify their spectral drift with some numerical values (section II). After that, we present some experimental results for an experimental optical 42.6 Gbps PSBT transmission system (presented in section III.1). The extent to which the detuning effect (equivalent of an MZI peak frequency drift) degrades the BER is demonstrated by experiments, and we finally give some numerical recommendations (section III. 2) to guarantee the stability of the MZI device ensuring no BER fluctuations.

II. MZI Thermal Model and Drift Calculus

1. Spectral Behaviour of MZIs

Mach-Zehnder interferometers are well known interferometric structures characterized by a temporal "add and delay" function, equivalent to a cosine shaped spectral response $H(\Delta\varphi)$ (or $H(\nu)$) given by (1) for the constructive port

$$H(\Delta\varphi) = \frac{1+\cos(\Delta\varphi)}{2}. \tag{1}$$

In (1), $\Delta\varphi$ is the differential phase of the waves travelling in the two arms of the interferometer. This differential phase is obtained with $\Delta\varphi = \beta\Delta L$ where ΔL is the differential length and β is the propagation constant of the wave. For MZIs used as DPSK demodulators, $\Delta\varphi = \omega\cdot\tau = \omega\cdot T_b$. In this expression, τ is the delay (equal to the bit duration T_b in DPSK applications) and $\omega = 2\pi\nu$, where ν is the optical frequency. As the MZI spectra have a periodic shape, the spectral periodicity is a major characteristic called the free spectral range (FSR). The FSR is equal to $1/\tau$.

2. Model for Thermal MZI Drift

If the interferometer is in a variable temperature (written as T in (3)) environment, two effects will induce a frequency shift on the interferometer transmission spectra: the thermo-optic effect (TOE) and the thermal expansion effect (TEE). The thermo-optic effect modifies the value of the core index, resulting in a variation of the effective index δn_{eff}, thus inducing a variation of the propagation constant $\delta\beta$. Thermal expansion effect implies a phase variation induced by the differential length variation $\delta(\Delta L)$. The variation of the differential phase between the two arms obtained by these two effects is finally given by (3).

$$\Delta\varphi = \beta\cdot\Delta L \Rightarrow \delta(\Delta\varphi) = \underbrace{\delta\beta\cdot\Delta L}_{TOE} + \underbrace{\beta\cdot\delta(\Delta L)}_{TEE} \tag{2}$$

$$\delta(\Delta\varphi) = \frac{2\cdot\pi}{\lambda}\cdot\delta n_{eff}\cdot\Delta L + \beta\cdot\alpha_t\cdot\Delta L\cdot\delta T \tag{3}$$

In (3), α_t is the thermal expansion coefficient, equal to $0.55\times10^{-6}\,K^{-1}$ for the single mode fiber (SMF 28). The effective index variation due to a small thermal shift δT is δn_{eff}, and the wavelength is λ. The calculus of δn_{eff} is obtained with the first order approximation $\delta n_{core/cladding} = \chi_t\cdot n_{core/cladding}\cdot\delta T$, and after that, δn_{eff} is calculated for the LP01 mode, where χ_t is the thermo-optic coefficient, evaluated at 8.6×10^{-6} by [10].

This thermal drift shows that MZI filters need to be temperature-stabilized when used as passive structures for DPSK demodulation or PSBT optical encoding. Moreover, optical PSBT encoding needs the MZI to remain centered at its transmission peaks. Therefore, if a Mach-Zehnder interferometer is thermally insulated from exterior fluctuations, a second system is needed to maintain the transmission peaks on ITU channels (for the constructive port in both DPSK and PSBT applications). This second adjustment is obtained by applying a supplementary phase shift in one arm, obtained by the heating of one arm of the interferometer.

The implementation of this system must be without mechanical constraints to ensure a low sensitivity of the whole

MZI device to polarization effects, usually quantified for optical filters as differential group delay or PD-λ [11] (PD-λ = polarization-dependent wavelength: specification of the maximal frequency shift between all polarization states at the input of the component). A second reason justifying the constraint-loss criteria for the heating system is that a large number of expansions/contractions due to the heating could break the interferometer arm.

3. Description of the 49.5 GHz Fiber-Fused MZI Used in Section III

In order to test the all-optical PSBT encoding, we must use a temperature-stabilized MZI. For this application, an accurate temperature stabilization process has been developed which consists of

- a general regulation circuit which stabilizes the temperature for the whole MZI device by packaging the MZI device in an aluminium box stabilized with Peltier elements;
- a local heating system without mechanical constraints to adjust the centre of the MZI on a 50 GHz frequency range.

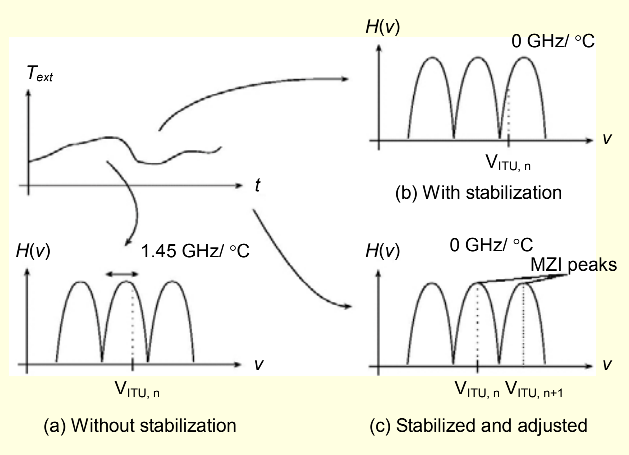
Figure 1 summarizes the stabilization process: when the exterior temperature (T_{ext}) fluctuates, the MZI peaks fluctuate from left to right with a 1.45 GHz/°C drift coefficient.

In Fig. 1(b), the general MZI insulation reduces exterior temperature fluctuation on the MZI; the peaks present no more frequency shifts, but the peak frequencies do not correspond to the ITU frequencies.

In Fig. 1(c), the local heating system produces the phase shift required in one of the MZI arms for the adjustment of the MZI peaks on the ITU grid.

Another important point of the thermal stabilization process is the accuracy obtained when the general stabilization of the MZI is operating (Fig. 1(b)). In Fig. 2, the evolution of the output power (for a constant wavelength) of the MZI is plotted versus time during the stabilization process. At first ($t \in [0;1500]$ seconds), the output optical power fluctuates with the fluctuation of the MZI package temperature as the MZI spectra shifts from left to right. After that, we can say that when stabilized (after around 2 hours and 20 minutes), the output power remains constant showing a good stabilization accuracy of the whole MZI ((S) zone in Fig. 2).

Finally, it is also necessary to point out that the fiber temperature can not be measured in our system. Thus, it is the MZI package temperature which is represented in Fig. 2(a). Nevertheless, as the stability criteria of the MZI is the stability of output optical power at a constant wavelength, we can conclude with Fig. 2(b) that the interferometer is well stabilized.



(b) With stabilization

(a) Without stabilization

(c) Stabilized and adjusted

Fig. 1. Thermal stabilization process: (a) no stabilization, (b) general regulation, and (c) fine adjustment provided by the differential heating system. T_{ext} is the exterior temperature.

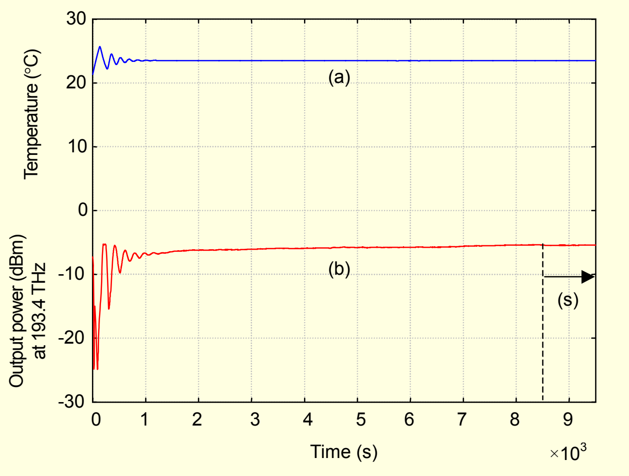


Fig. 2. Thermal stabilization process: (a) temperature of the MZI package and (b) output optical power at 193.4 THz.

The system is slow but is characterised by good stability over a long stabilization time. A less than 0.1°C accuracy has been obtained over many hours and the experiments in section III were made during the stabilized state (S). As a conclusion, the MZI is considered to be stabilized enough for experiments. This conclusion can also be justified by the fact that during all experimental measurements presented in section III (including possible environmental fluctuations like exterior temperature), the PSBT optical spectra shown in Fig. 4(d) remain stable, demonstrating the good stabilization of the MZI.

By plotting the evolution of the output transmission peak power for an MZI with a 49.5 GHz FSR (ΔL = 0.41 cm), we determined the thermal periodicity of maximum transmission power. We found a 34.2°C period, thus giving the drift coefficient 1.45 GHz/°C of the MZI device.

Finally, it is important to note that during the temperature stabilization process, the FSR remains constant, and a simple calculus can justify this result. For example, we shall consider an MZI with a 50 GHz FSR at 20°C. This MZI will have a delay equal to $\tau = 20$ ps, and a differential length ΔL equal to 4.108 mm. If the temperature increases by $\Delta T = 50$°C, the TEE will induce a $\Delta L \cdot \Delta T \cdot \alpha_t = 4.108 \cdot 50 \cdot 0.55 \times 10^{-6} \approx 1.1 \times 10^{-4}$ mm variation on ΔL value. The new value for ΔL at 70°C will be 4.108 + 0.00011 = 4.10811 mm, thus giving a new delay equal to 20.0005 ps, and an FSR equal to 49.999 GHz. As this reduction of the FSR value is negligible, the FSR can be considered as constant during temperature stabilization.

III. Experimental Setup Using Optical PSBT

1. Setup Description

Figure 3 shows the experimental setup used for the experimental PSBT transmission. Four binary streams with 10.65 Gbps data rates are generated and multiplexed to form a 42.6 Gbps binary signal (data). The data and complementary data created by a D flip-flop are launched into two identical drivers, each driving one of the two electrodes of a dual-drive modulator.

The driving conditions of the dual drive modulator used here are the same as described in [12] for DPSK transmissions. More precisely, the bias point is set at the minimum of the power transmission curve, and as the $LiNbO_3$ Mach-Zehnder modulator is Z-cut, the push-pull configuration is used to minimize chirp.

No precoding section is used in this experiment to keep the pseudo-random binary sequence (PRBS) nature (2^{23}–1 length) of the data signals. The optical data output resulting from this setup is in DPSK format. In order to convert it into the PSBT format, the optical data stream is launched into the fiber-fused optical interferometer described in preceding sections, in which the differential delay between the arms is equal to $\tau = 0.86 \cdot$bit time $= 0.86 \cdot T_b = 20.2$ ps (FSR = 49.5 GHz).

Another important point is the justification of the $0.86 \cdot T_b$ choice for the MZI delay. Due to the reduced size of the optical spectrum of PSBT format, implementation of OC-768 channels in a deployed OC-192 architecture is possible and was experimentally tested last year in [13] with promising results.

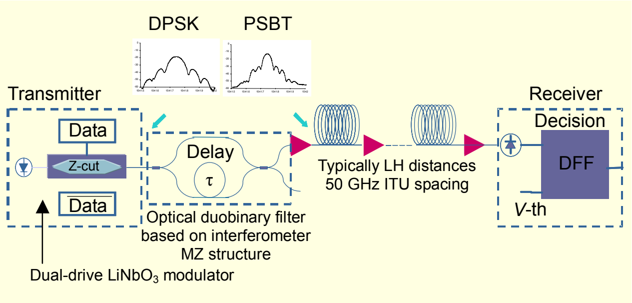


Fig. 3. Experimental setup of the PSBT transmission system.

One key point in transmission link upgrades is to perform with an increased capacity on the same frequency grid. As PSBT can be transmitted on a 50 GHz grid spacing [8], it will be very attractive to have only one MZI filter for DPSK to PSBT conversion on multiple wavelengths. With this condition, the FSR should be 50 GHz, the same value as the grid spacing. For a 50 GHz FSR, the MZI delay is equal to $\tau = 20$ ps. Finally, considering a 42.6 Gbps transmission (OC-768 + 6.5% forward error correction), we have $T_b = 23.5$ ps, thus giving the relation $\tau = 0.85 \cdot T_b$. As a conclusion, a 50 GHz value for the MZI FSR ensures the WDM compliance: it performs a multiple wavelength conversion from DPSK to optical PSBT.

The all-fiber MZI is characterized by the values given in Table 1. In this table, the isolation ratio is the interference contrast of the interferometer, and the uniformity is the maximal power difference between the MZI transmission peaks. Moreover, the FSR value of the MZI used in the experiments is 49.5 GHz and not 50 GHz. Such an FSR gives $\tau = 0.86 \cdot T_b$ but this is sufficient for the creation of the PSBT effect. This has been experimentally confirmed in [8], where the same optical filter led to a large increase in GVD tolerance. Finally, as the experiment presented here takes place in a single channel configuration, no constraint is required for WDM 50 GHz grid compliance.

At the receiver end, an opto-electronic conversion is carried out by launching the optical signal into a 40 GHz photodiode matched to a high sensitivity DFF [14]. The electrical signal at 42.6 Gbps is then demultiplexed into four 10.65 Gbps tributaries on which the BER measurements are performed.

The DPSK optical eye diagram and spectrum obtained at the output of the $LiNbO_3$ modulator in front of the optical fiber-based interferometer are shown in Fig. 4(a) and 4(b). A small amount of noise and jitter affects these eye diagrams. This should be only due to the receivers and clock recovery circuits since the optical spectra have a low level of noise.

Table 1. Characteristics of the 49.5 GHz fiber-fused interferometer used.

Isolation (dB)	25
Uniformity (dB)	0.4
DGD (ps)	0.5
Delay (ps)	20.2
FSR (GHz)	49.5

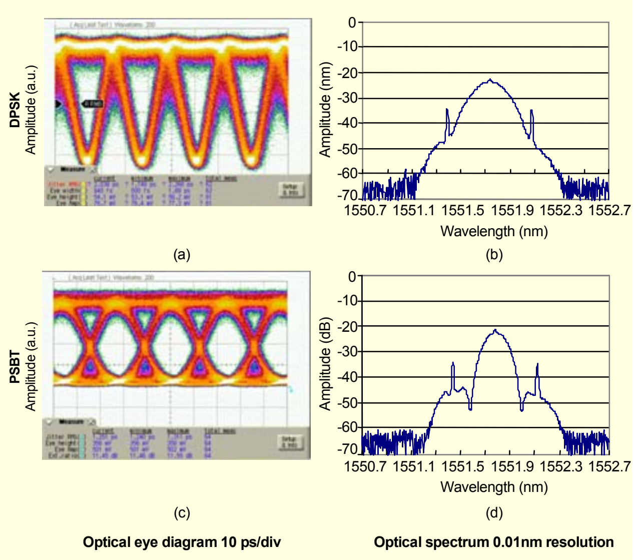


Fig. 4. Optical eye diagram and spectrum at input (a), (b) and output (c), (d) of the 49.5 GHz fiber-based Mach-Zehnder interferometer.

At the output of the MZI filter, we obtain an NRZ-like duobinary eye diagram as in Fig. 4(c) and observe an optical spectrum of reduced size as in Fig. 4(d), corresponding to the MZI filter spectral width.

2. Detuning Effect

In order to evaluate the effect of inaccurate thermal stabilization, resulting in a frequency shift in the MZI peak frequencies, we used the 49.5 GHz fiber-fused interferometer described in the preceding sections, which contains an accurate thermal stabilization (precision < 0.1°C, ensuring an MZI spectral stabilization better than 0.14 GHz).

The laser used (193.2 THz, ITU C-23) was frequency adjusted to create the detuning which is the difference between the laser frequency and the MZI frequency peak value. We studied the evolution of BER (back to back measurements: fiber length = 0 km) with the laser frequency value. Results were plotted as in Fig. 5.

We observed that, as could be expected, the detuning values directly affect the values of the measured BER. More precisely, low detuning values induce severe degradations of the BER values. For example, for a 24 dB optical signal-to-noise ratio (OSNR) (here equivalent to a 10^{-9} BER value without detuning, point A in Fig. 5), a 2 GHz shift from the optimal value induces a BER that is 10 times higher (point B), and a 5 GHz detuning value leads to the 2.10^{-6} BER value (point C).

These values are reduced for lower OSNR. At BER $\approx 10^{-5}$ (point D, OSNR = 19.5 dB, no detuning), a 5 GHz frequency shift is enough to degrade the BER by a factor of 10 (point E).

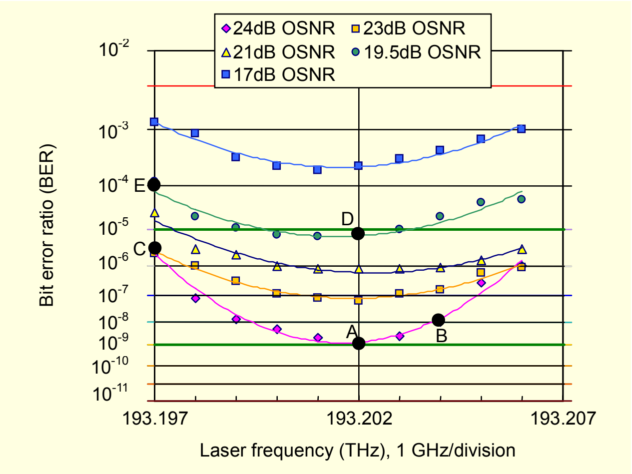


Fig. 5. BER evolution with laser frequency value. Different OSNR values have been considered for these experiments.

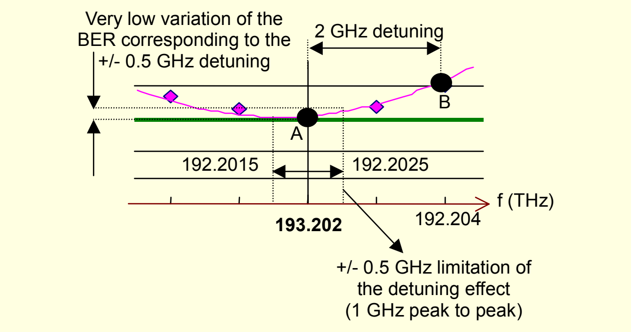


Fig. 6. Enlargement of the Fig. 5.

The detuning effect appears to be very important, so an inaccurately stabilized MZI will induce large BER fluctuations throughout the whole transmission system.

IV. Conclusions

In this paper, we experimentally studied, for the first time to our knowledge, the tolerance of the detuning effect for a PSBT optical transmission: at low BER values (10^{-9}), a 2 GHz shift can induce severe BER fluctuations in the detected signals. In section II we calculated the relationship between the temperature and the MZI peak frequency shift, leading to the theoretical value 1.45 GHz/°C for the MZI used here (49.5 GHz periodicity).The experiments described in section III showed that when Mach-Zehnder interferometers were used in PSBT transmissions, an accurate BER stabilization could not be obtained without limitation of the detuning effect. Good performance results have been obtained when the detuning effect is limited to less than 1 GHz (peak to peak variation). This ensures an MZI frequency peak stabilized with a 0.5 GHz precision (+/- 0.5 GHz around ITU frequency, as indicated in

Fig. 6) and a BER variation strongly limited according to Fig. 5 and Fig. 6. Such a value (1 GHz variation) corresponds to thermal stabilization accuracy around 0.7°C. Our conclusion is that a 0.5°C stabilization accuracy (ensuring a 0.73 GHz peak-to-peak limited MZI drift) guarantees that the MZI will not be the source of BER fluctuations during the conversion from a DPSK modulation format into an all-optical PSBT.

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