Frequency reference dissemination across deployed fiber networks

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Abstract. The precision and stability of frequency standards is an important factor in many scientific and technological areas. Most of the applications involved require the transmission of those standards at short or longer distances with unprecedented stability. The most prominent method to achieve the required stability is the transmission through optical fibers. Round trip control loops are implemented to compensate the transmission imposed phase shifts due to temperature fluctuations and mechanical perturbations. Regenerators are often required in long distance links to prevent excessive noise accumulation. Moreover, deployed optical networks are subjected to back – reflections which impose noise to the phase error signal of the control loop. An all optical regenerator based on dual mode injection locked laser is proposed and experimentally tested, which resonantly amplifies the incoming modulated optical signal and provides wavelength conversion for the back - propagating control signal to distinguish it from the reflections.

The transmission stability is less affected by phase noise if higher frequency is used. Two methods for increasing the frequency of the transmitted microwave standard were proposed. The first introduces the use of double sideband suppressed carrier modulation which effectively doubles the operating frequency and the second an opto-electronic frequency divider, which scales down high mmwave frequencies using fractional frequency division. The stability and low phase noise characteristics of the signal produced at the receiver were experimentally verified. This divider is also capable of synthesizing mmwave frequencies, exhibiting superb phase noise performance.

Another category of frequency standard dissemination schemes focuses on the phase error compensation at the receiver, based on the temperature dependence of the fiber dispersion. Two one-way transmission solutions have been proposed, a phase sensitive amplifier which translates the temperature induced phase drift into output power fluctuations and a phase modulation process which bridges the frequency gap between distant optical tones.

Keywords: frequency stability, optical fiber networks, optical injection locking, optical frequency division, phase stabilization.

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* Dissertation Advisor: Dimitris Syvridis, Professor.

1 Introduction

The precision and stability of frequency standards is rapidly improving, aiming to boost experiments in fundamental physics and leverage the performance of technologies such as global positioning system, telecommunication networks and radio telescope array synchronization, long baseline interferometry and quantum networking. The possibility of comparing frequency standards produced from distant sources is of special scientific and technological interest. Furthermore, the synchronization of radio telescope antennas and telecommunication networks require the transmission of frequency standards at long distances with great stability. Optical fibers are the best medium for frequency standard dissemination as they are immune to electromagnetic interference and are less delicate to environmental perturbations. Nevertheless, the refraction index and consequently the group delay depend on temperature and mechanical stress, resulting in phase instability at the receiver.

To maintain the required stability through the transmission link, a round trip control loop is implemented where the transmitted and the round-trip signal are compared and the phase error extracted is used to actively cancel out the phase jitter. Thermal fiber spools and fiber stretchers have been employed as actuators for slow and fast phase variation correction respectively [1]. To ensure that the corresponding phase error has also been corrected at the receiver, the forward and return paths must suffer exactly the same amount of phase shift. Internal reflections at fiber interconnects, polarization mode dispersion and stimulated Brillouin scattering (SBS) impose different phase errors in the two paths [1, 2]. Various techniques have been proposed to overcome this issue, based on microwave or optical frequency differentiation of the waves travelling in forward and backward directions [1, 2, 3]. The optical frequency (i.e. wavelength) differentiation solution resolves both SBS and interconnection reflection issues. The wavelength separation of the forward and round-trip optical carriers must be large enough to easily separate the two wavelengths using cheap optical filters [1].

For long distance frequency dissemination, regenerator nodes are required to provide acceptable signal to noise ratio (SNR) and high loop bandwidth, especially for cascaded optical links via the telecommunication network [4]. These nodes often use Erbium Doped Fiber Amplifiers (EDFAs). If different wavelengths are employed, apart from the regeneration of the propagating wave, a new wavelength carrying the RF reference must be back-propagated for the compensation of the preceding span. In the context of this dissertation, an all optical signal regenerator is proposed which not only resonantly amplifies the incoming modulated optical carrier but also provides wavelength conversion for the back - propagating signal to distinguish it from the reflections. The regenerator is based on dual mode injection locked laser. The laser operation was simulated and the regenerated signal stability was experimentally verified in a cascade link of two fiber spans.

Another factor degrading the absolute stability of the disseminated frequency standard, apart from the phase noise induced by the link, is the noise imposed by the optical and electronic components involved. The most important figure of merit characterizing the link performance is the fractional stability which is defined as the ratio of the absolute stability divided by the frequency. The fractional stability is substantially improved when a higher frequency standard is used [1]. Moreover, the phase error voltage used to stabilize the delay locked loop is magnified and the phase discrimination sensitivity is enhanced, when a higher microwave frequency is used, improving the phase correction performance and thus the stability of the received standard. Higher microwave frequencies can be used directly from proper sources or by multiplying a lower microwave frequency prior to transmission. The main drawback associated with higher frequency transmission is the increased cost, mainly attributed to the cost of the electro-optical conversion components, like modulators and photodiodes. For simplicity and better performance, the intensity modulation - direct detection (IM-DD) scheme has been adopted in optical transfer of microwave frequency standards. As fiber dispersion alters the phase relationship among the modulation sidebands, the beating of the optical carrier with the sidebands in the remote photodiode results in periodic spatial amplitude fading of the detected microwave signal. Dispersion compensation techniques are required to alleviate this problem but the link losses are increased.

Double sideband suppressed carrier (DSB-SC) modulation is proposed in this work to effectively double the frequency at the receiver, without using a wide bandwidth electro-optical modulator. Moreover, the dispersion induced spatial fading is vanished using this modulation format.

Following the achievements of the previous method, the feasibility of transferring even higher, mmwave or THz frequencies was investigated. The outcome of this effort was an opto-electronic frequency divider which does not require high bandwidth components, does not impose excessive phase noise and is capable to downscale those high frequencies using fractional frequency division. In this way, any desirable final electrical frequency can be selected, preserving the stability of the higher reference frequency transmitted through the link. This divider is also capable of synthesizing high microwave and mmwave frequencies.

Optical generation of microwave and mmwave frequencies is considered the ultimate method for obtaining the required features of stability and spectral purity [5]. High speed photodetectors can generate high frequencies from the beat produced by optical tones, with the output frequency limited only by the bandwidth of the detector. Optical frequency combs (OFCs) produced by femtosecond mode-locked lasers or micro-resonator Kerr based combs have been used for generating the required high stability optical tones. Optoelectronic microwave oscillators have also been introduced for generating electrical frequencies of superb spectral purity but with limited tunability when using a specific energy storage element and upper frequency limited by the electro-optical modulator response [6].

Other methods like optoelectronic frequency multiplication, optical phase locking and optically referenced electronic synthesizers have been proposed for photonic generation of the mmwave frequencies. State of the art heterodyne optical phase-locking on chip techniques [7] include an OFC reference and combine an offset frequency free running electronic oscillator to achieve the required tunability. A slave laser is locked to one of the OFC tones detuned by the electronic oscillator frequency and the phase noise of the free running oscillator is added to the phase noise of the selected comb harmonic frequency.

In this dissertation, a mmwave generation method based on novel optoelectronic phase locked loop (PLL) is proposed. This synthesizer takes an optical comb reference of high stability as an input and provides wide operating frequency range, multiband operation and high resolution. It does not use free running electronic oscillators and all required frequencies are locked to the reference. Moreover, it is implemented using modulators, photodiodes and passive optical components. Unlike the optical phase locking techniques, there is no need for high loop bandwidth.

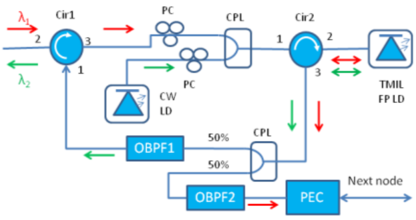
The majority of published works utilizes the loop-back link configuration in which the original reference is compared with the round-trip signal to determine the phase variations and apply corrective actions that maintain the stability of the transmission system. This technique is by far the most accurate provided that the reference and the round-trip signal travel through the same optical fiber, thus experiencing the same propagation delay.

The requirement of the bi-directional transmission along the same fiber, however, poses many challenges. Firstly, modern communication systems operating in installed fibers do no support bidirectional propagation. Bi-directional transmission is also very sensitive to back-reflections and back-scattering (including Rayleigh scattering). Further, the round-trip time poses physical constrain on the bandwidth of the compensation technique. This makes these techniques impractical for long-distance applications. Additionally, bi-directional techniques are not easily applied in scenarios where multiple remote sites must be precisely synchronized with a central point distributing time and frequency references in applications like very long base line interferometry (VLBI), and deep space networks (DSN). Lately, the use of stable long-distance fiber links is becoming especially attractive for multi-node quantum networks [8] for which bi-directional schemes may not be suitable due to the possible contamination of quantum signals by backward-propagating error signal. For all these reasons, many research groups have tried to replace the bi-directional schemes with the "one-way" approach in which the remote end will have all the required data in the form of phase error to act as an active compensator of non-deterministic propagation delay fluctuations. One-way schemes generally rely on the fact that environmental changes influence optical signal propagating at different wavelengths in a different way due to the sensitivity of chromatic dispersion on temperature [9]. This has been demonstrated by simultaneously disseminating a microwave frequency reference upon two distant wavelengths within the C-band [10]. The main drawback was that the error signal was very weak, not allowing for high-enough precision [10].

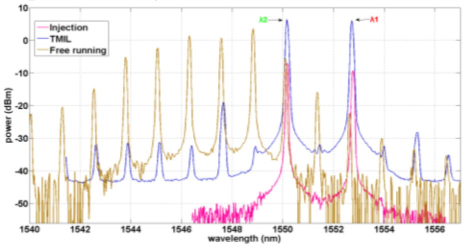
Two solutions for one-way transmission with enhanced sensitivity have been proposed in this work. In the first one, a three tone reference comb is transmitted. At the receiver, the optical tones are inserted into a phase sensitive amplifier - PSA, in which the phase relation between the tones affects the gain of the amplifier and so translates the temperature induced phase drift into output power fluctuations and finally to phase error voltage. The second one uses the same three tones at the transmitter and bridges the frequency gap at the receiver by phase modulating the central tone with high modulation depth. The modulating electrical frequency is produced at the receiver and is not required to be of high stability as its phase noise manifests as common mode in the phase error extraction process. The sensitivity of this method is the identical to the previous one and is achieved using much lower optical power. This feature is very desirable in quantum network synchronization.

2 All optical regenerator for long distance stable fiber delivery of radio frequency standards

In this work, a novel intermediate node and receiver architecture for the dual wavelength approach is proposed, based on the Two Mode Injection Locking – TMIL technique [11, 12]. This approach combines simplicity with enhanced performance, scalability and transparency to the modulation frequency relative to the existing solutions. Fig. 1a depicts the receiver-regenerator. The incoming optical wavelength λ_1 is intensity modulated with the sinusoidal frequency standard. With the use of a fiber coupler, it is combined with the CW wavelength λ_2 and both are injected to the FP laser through circulator 2, at two different lasing modes. Wavelength conversion and reproduction to λ_2 and optical regeneration of the original sinusoidal microwave frequency standard carried in λ_1 takes place in the FP laser, based on the two mode injection locking mechanism [13]. The optical spectrum of the free running and injection locked FP laser and the injected signal are depicted in Fig. 1b.



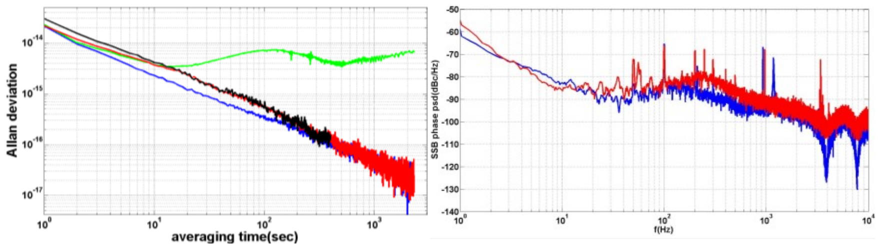
(a)



(b)

Fig. 1: (a) The proposed all optical regenerator for microwave reference frequency dissemination, (b) the optical spectrum at the input (red) and the output (blue) of the regenerator. The free running F/P laser is also depicted (brown)

The FP laser output is split in two parts, each of which passes through an optical band pass filter in order to isolate the forward path from the return path and vice versa. The wavelength λ_2 is sent back to the transmitter node through the OBPF1 and circulator 1 playing the role of the reference signal for the link stabilization at the transmitter side. Wavelength λ_1 is isolated from λ_2 with the use of OBPF2 and is directed to the next node after passing through the phase error correction system. If the current node is the last one, the output of OBPF1 will be connected to a photodiode in order to retrieve the frequency standard. The stability of the received standard is depicted in terms of Allan deviation and phase noise in Fig.2a and Fig.2b respectively.

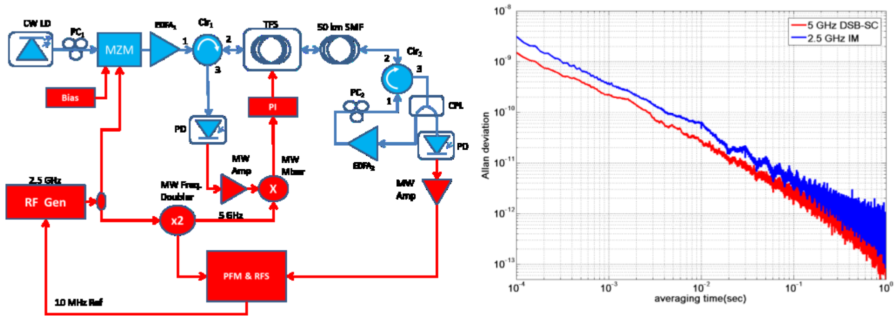


(a) (b)

Fig. 2: (a) Allan Deviation. Blue: Electrical noise floor, Green: IM open loop, Red: IM closed loop, Black: Receiver-Regenerator closed loop, (b) SSB phase noise. Blue: IM open loop, Red: Receiver-Regenerator open loop.

3 Double sideband suppressed carrier modulation

Next, the microwave frequency standard fiber transmission architecture based on Double Sideband Suppressed Carrier – DSB-SC modulation format is investigated. Apart from immunity to dispersion, the scheme proves to be advantageous with respect to other techniques as doubles the initial frequency and provides high modulation depth [14].



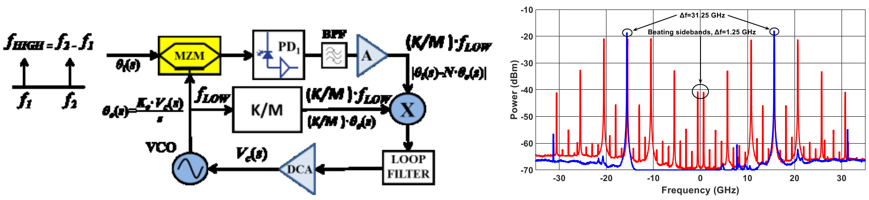
(a) (b)

Fig. 3: (a) DSB-SC Transmission, (b) Short term stability, open loop, non-overlapping Allan deviation for optical DSB-SC 5 GHz and IM 2.5 GHz transmission.

A basic high precision frequency of 2.5 GHz is produced by an RF generator that is referenced to a rubidium standard source. The basic RF frequency is applied to a Mach Zehnder modulator, biased at its minimum transmission point. The resulting optical DSB-SC signal is amplified and sent through a circulator and Thermal Fiber Spool actuator to a 50 km long Single Mode Fiber Spool. At the receiver, a photodiode detects the microwave reference at 5 GHz and drives it to the Phase-Frequency Measurement unit. At the transmitter end, the detected round trip RF signal is amplified and sent to a microwave mixer, along with the locally generated and doubled to 5 GHz frequency reference. The retrieved error voltage is fed to a PI controller that drives the thermal spool actuator in order to compensate the thermally induced phase error. In order to compare the open loop DSB-SC 5 GHz system's performance relative to the standard 2.5 GHz intensity modulation format, Allan deviation has been measured in short time scale and depicted in Fig. 2(b). Allan deviation figures using DSB-SC are nearly halved compared to the conventional IM-DD method and the fractional stability is doubled accordingly.

4 Optoelectronic frequency divider and synthesizer

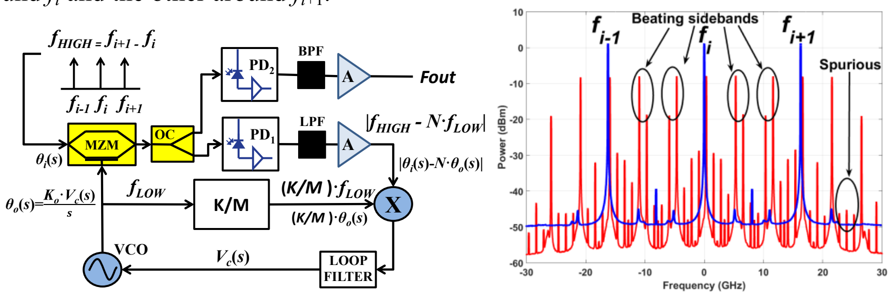
Since fractional stability is inversely proportional to the absolute frequency, it is preferable to disseminate high microwave frequency references. Disadvantages of this approach are the requirement of high bandwidth optoelectronic components for the detection and utilization of the disseminated reference and the limited usability as reference of the mmwave frequencies. In this work, a technique that circumvents this issue is proposed. The scheme depicted in Fig. 4a divides a high mm-wave frequency f_{HIGH} corresponding to the spectral spacing of two optical tones, by generating a comb of a fractional sub-multiple frequency (f_{LOW}) spaced tones, using a practical method relying on an optical modulator and low-frequency electronics. The phase noise of f_{LOW} is much lower than the f_{HIGH} phase noise, as expected at the output of a frequency divider. The optical spectrum in Fig. 4b contains multiple sidebands. The beating of those sidebands on a high bandwidth photodiode can provide a variety of electrical frequencies in multiple frequency bands [15, 16].



(a) (b)

Fig. 4: (a) The optoelectronic frequency divider, (b) the optical spectrum at the MZM output

The modified divider – frequency synthesizer is depicted in fig. 5a. The synthesizer's high frequency reference f_{HIGH} corresponds to the spacing of an optical frequency comb - OFC. The OFC is launched into a Mach Zehnder Modulator (MZM). A voltage controlled oscillator (VCO) generates a tunable lower frequency as a submultiple of f_{HIGH}, the so-called f_{LOW}, which modulates the OFC lines in high modulation depth, producing f_{LOW} spaced combs around each principal OFC line (Fig. 4b). Thus, the beating of these sidebands provides a frequency term roughly equal to $(K/M)\cdot f_{LOW}$ which can be detected by a low bandwidth photodiode (PD_1). The detector's photocurrent is filtered to reject higher frequency beating products, amplified and fed to an RF phase detector along with the output of the VCO electrically divided by the ratio K/M. The K/M frequency division process can be implemented by a variable reference direct digital synthesizer (DDS). The output of the detector is the loop error voltage which after filtering drives the VCO in order to achieve precise locking of the local f_{LOW} to the incoming f_{HIGH}. In this respect, the output obtains the fractional stability of the initial comb at the frequency of preference. The MZM output (Fig. 5b) contains optical tones which extend up to a bandwidth of at least $L{\cdot}f_{HIGH}$ where L is the number of the reference comb lines. The beating of these tones in a fast photodiode (PD_2) can provide a variety of electrical frequencies. Some of these frequencies are harmonically related to f_{HIGH}, ($n{\cdot}f_{HIGH}$) produced from the beating between sidebands of the same f_{HIGH} spaced comb around any f_i. Other frequencies offset from the f_{LOW} harmonics are generated from the beating of sidebands coming from distant comb lines, i.e. one around f_i and the other around f_{i+1}.



(a) (b)

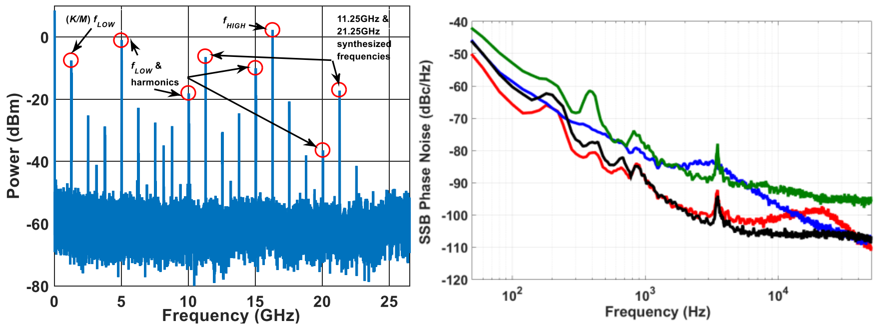
Fig. 5: (a) The synthesizer loop. Laplace transform expressions are provided, (b) the optical spectrum of the reference comb (blue) and the spectrum after the modulation by f_{LOW} (red), in locked condition. f_{HIGH} = 16.25GHz, f_{LOW}=5GHz, $f_{LOW} = f_{HIGH}/(N+(K/M))$, N=3, K=1, M=4.

The generated frequencies at the output of PD_2 read as

$$f_{out} = (i-1)\cdot f_{HIGH} \pm j\cdot f_{LOW} = [(i-1) \pm \frac{j}{N \pm (\frac{K}{M})}]\cdot f_{HIGH}$$

i=1…L and j=0…R, R being the number of f_{LOW} offsets from the reference comb tones, produced by the f_{LOW} driven MZM. The desired frequencies can be selected with band pass filters at the electrical domain. The microwave or mmwave bandpass filters have to reject products that are spaced at least $(K/M){\cdot}f_{LOW}$ or $(1-(K/M)){\cdot}f_{LOW}$ from the desired frequency, so in selecting the value of f_{LOW} one must take into consideration the available filter bandwidth and roll - off characteristics. Suitable mmwave filtering solutions are described in [12]. The requirements for filtering are relaxed if N is a small integer which translates to higher f_{LOW} spacing and the K/M ratio is close to 1/2. In this case, the spurious frequencies that have to be rejected are separated from the desired ones by roughly $f_{LOW}/2$. More advanced but also more complex techniques that could be used to achieve better spurious and noise suppression is applying optical filtering using MZI filters [13] supplementing the electrical filtering or injection locked lasers [3, 14], which apart from selectivity, also provide high optical power to the beating photodiode and consequently enhanced C/N ratio.

The electrical frequencies that are generated from the beating optical tones are depicted in Fig. 6a. The amplitudes of these frequencies depend on the optical power of the optical tones and the number of optical tone pairs which are beating to produce it.



(a) (b)

Fig. 6: (a) The electrical spectrum at the fast photodiode output, (b) Measured SSB phase noise. Blue: unlocked VCO at 5 GHz, red: locked VCO, black: reference generator at 5 GHz. Green: 21.25 GHz synthesized tone.

In order to characterize the short term stability of the synthesizer, we carried out phase noise measurements at 5 GHz, both for the frequency standard used to generate the f_{HIGH} spaced reference tones and the VCO output. The results depicted in Fig. 6b show that the phase noise of the locked VCO frequency is roughly equal to that of reference within the PLL bandwidth, while the phase noise of the free running VCO is higher than that of the reference at 250 Hz and above. The phase noise profile of the 21.25GHz tone is well matched to the reference and is stronger than that of the locked VCO at f_{LOW}=5GHz as this synthesized frequency is considerably higher than f_{LOW}. The plateau of -95 dBc/Hz is observed due to the reduced photodiode output power at 21.25GHz.

5 One way phase discrimination using phase sensitive amplifier

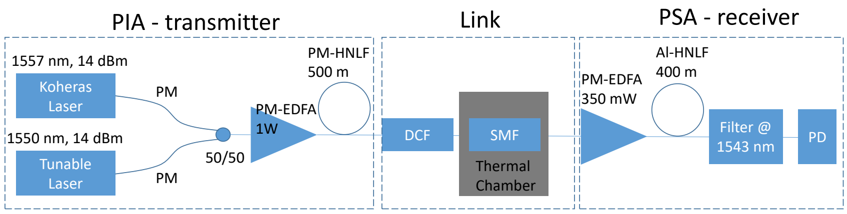


Fig. 7: Experimental Setup: All components are pigtailed with polarization maintaining fibers.

The optimum way to enhance the sensitivity in one-way systems is to perform the phase comparison in the optical frequency domain using a phase sensitive amplifier – PSA at the receiver [17]. A proof-of-concept experiment was carried out in order to verify the high sensitivity theoretically predicted. The set-up is shown in Fig. 7. Three widely spaced optical tones are required at the transmitter. A phase insensitive amplifier (PIA) in a 500 m HNLF was employed to generate the third, idler tone at 1543 nm with the same power as that of the signal tone (at 1557 nm) [12-14]. The three waves

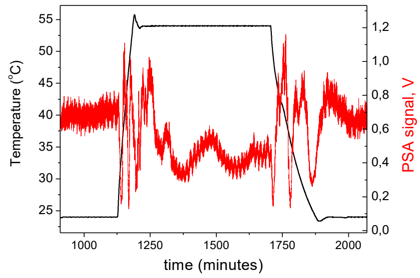
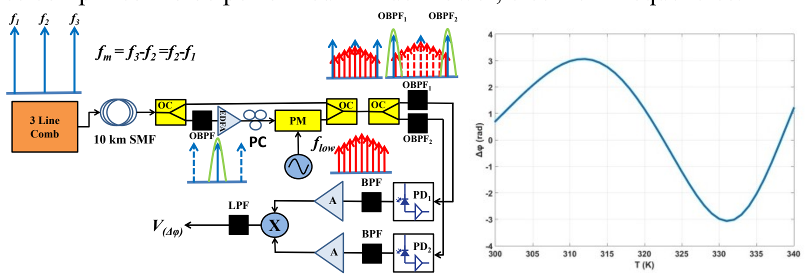


Fig. 8: PSA signal as a function of the thermal chamber temperature. Large changes occurring when temperature increased/decreased have magnitude of about 3 periods.

propagated first through a DCF and then through the 10 km long SMF which is put in a thermal chamber for the investigation of PSA gain when the fiber is under thermal fluctuations. The PSA on-off gain was found to be 10 dB which was sufficient to demonstrate the properties of the PSA based temperature sensor (Fig. 8). The wavelength detuning is 7 nm. The DCF module was kept inside a polystyrene box in order to protect it from temperature variations applied on the SMF fiber. The temperature of the thermal chamber was varied between 24°C and 54°C and the PSA gain was detected at the idler wavelength. The PSA gain of 10 dB max-min swing exhibited fluctuations corresponding to almost 3 periods as temperature increased from 24°C to 54°C and the same for decreasing back to 24°C. This corresponds to a $\Delta\varphi/\Delta T$ coefficient of 0.62 rad/Kelvin. This value is significantly higher than the one attained using previously-published schemes [9, 10].

6 One way phase discrimination using phase modulation

A novel method transferring the accuracy of one way optical domain discrimination techniques to electrical frequencies is also proposed. The scheme is depicted in Fig. 9a. As in [17], three optical tones with frequency separation of f_m, corresponding to a few nm in C band, are transmitted through SMF fiber. At the receiver, the center line with optical frequency f_2 is isolated, amplified and phase modulated by a lower frequency f_{low} generated by a conventional RF source. The modulation depth is adjusted to provide sidebands with adequate power close to the f_1, f_3 lines. Next, the phase modulated signal is coupled with the two unmodulated tones. The resulting signal is split in two parts and undergoes optical band-pass filtering around f_1, f_3. The two filtered optical signals contain at least the optical tones at f_1, f_3 and adjacent modulation sidebands $f_2 \pm n \cdot f_{low}$, which are beating in each of the two low bandwidth photodiodes PD_1 and PD_2. The detected electrical outputs are filtered around f_3-(f_2+$n \cdot f_{\mathrm{low}}$) = (f_2-$n \cdot f_{low}$)-f_1 = f_m-$n \cdot f_{low}$. The phase difference between these two equal microwave frequencies is the optical phase drift $\Delta\varphi(T)$ between f_1, f_3, caused by the temperature depended fiber dispersion. To detect the phase drift, the filtered signals are driven to a microwave mixer, after amplification. The DC output of the mixer is proportional to cos($\Delta\varphi$) and is isolated using an electrical LPF. In this way, the modulated f_2 tone bridges the frequency gap between the distant optical tones at f_1, f_3, allowing the optical phase comparison to be performed in much lower, electrical frequencies.



(a) (b)

Fig. 9: (a) One-way phase discrimination using phase modulation at the receiver, (b) The phase error vs temperature.

A simulation was carried out to evaluate the performance of the proposed scheme. The center frequency f_2 is set corresponding to 1550 nm wavelength, the frequency distance of the transmitted tones f_m is set to 181 GHz which is roughly 1.5 nm, f_{low} is 30 GHz and n=6, so the detected microwave frequency after beating is f_m- $n\cdot f_{low}$= 1 GHz. The transmitted three line comb is generated by a 100 KHz linewidth laser, intensity modulated by a 181 GHz source subjected to white phase noise of -70 dBc/Hz spectral density. The transmitted power is set to only 1 mW and the gain of the EDFA used to amplify the center line at the receiver is set to 12 dB with noise figure of 5 dB. Thermal and shot noise is added to the photodiodes. The temperature depended index of refraction is extracted using the Sellmeier coefficients for fused silica [12] and then feed the split – step Fourier model of propagation in a fiber length of 10 km. The f_{low} source is also considered noisy, with the same phase noise profile as in the case of f_m. The results are depicted in Fig. 9b. The achieved sensitivity is well fitted to that obtained in [17], while the error signal is clean, albeit the amplitude and phase noise contributions. It should be noted that the phase noise of f_{low} and f_m tones is proved to be common mode, not affecting the resolution and stability of the system. The launched power is minimal, adding to the simplicity of the scheme and ease of adaptation to the existing infrastructure.

7 Final Conclusions

This work has contributed in both bidirectional and one way fiber dissemination of reference frequencies technology. The proposed regenerator for long distance bidirectional links solves the reflection problems encountered in deployed networks. Two cost effective solutions offering enhanced stability by increasing the frequency standard were proposed and experimentally tested, the DSB-SC modulation format and the optoelectronic frequency divider. Regarding one way systems, two novel techniques for optical frequency phase comparison were introduced, offering considerable sensitivity enhancement.

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