Optics Communications 382 (2017) 182–185

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Double sideband suppressed carrier modulation for stable fiber delivery of radio frequency standards

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ARTICLE INFO

Article history:
Received 25 April 2016
Received in revised form
22 June 2016
Accepted 26 July 2016

Keywords:
Frequency standard
Radio frequency photonics
Analog optical signal processing

ABSTRACT

We theoretically and experimentally investigate the properties of a double sideband suppressed carrier modulation transmission scheme for long distance microwave frequency standard dissemination. The proposed method effectively doubles the transmitted frequency obtaining enhanced phase noise and stability performance. Suppressing the optical carrier also eliminates the dispersion induced signal fading. Important transmission parameters like optical modulation depth and linearity are also improved. Allan deviation and phase noise measurements prove the superior performance of the proposed modulation format.

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1. Introduction

Precision applications, such as atomic clock comparison and synchronization and long-baseline array synchronization of phase-coherent radio telescopes require distribution of high precision frequency standards [1]. Optical fiber has been extensively used for transmission, but random variations of the effective length due to environmental changes degrade the stability. Recent advances in frequency standard generation pose stringent demands. Enhanced performance of the optical transmission link is required in order to comply with the improved stability of the newly developed frequency standard sources [2].

The phase noise induced by the link and the optical and electronic components involved degrade the absolute stability of the disseminated frequency standard. But 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. As the induced phase noise is additive, the fractional stability is substantially improved when a higher frequency standard is used [1,2]. Optical frequency standards, although not directly applicable to microwave applications, provide ultimate fractional stability, as the frequency lies in the multi THz region.

The phase variations along the optical link are attributed to mechanical stresses imposed on the fiber and the thermal dependence of the fiber refraction index. The introduction of a feedback loop in the transmission link mitigates the induced phase variations. The transmitted and round-trip signals are compared in a microwave mixer and the phase error extracted is used to actively cancel out the phase jitter. Fiber stretchers and thermal fiber spools driven by the phase error voltage produced in the mixer are employed to cancel out these effects [3]. The phase error voltage is magnified and the phase discrimination sensitivity of the microwave mixer 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.

The stability performance is also dependent on the power of the signal. Optical modulation depth affects the Optical Signal to Noise Ratio – OSNR and consequently the electrical SNR and must be maximized for optimal power exploitation. However, as the driving RF voltage imposed on the electro-optical modulators is increased, harmonic frequency products emerge in both the optical and electrical domain, due to the non-linear transfer characteristic of the modulation process. These products spoil the spectral purity of the transmitted standard and must be filtered out at the receiving end.

Although the frequency of the disseminated signal and its power determine the ultimate stability of the system, one has to

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http://dx.doi.org/10.1016/j.optcom.2016.07.071
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take into account the transmission impairments and how they interplay with frequency. 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 [4]. Double Sideband Suppressed Carrier – DSBSC - modulation has been proposed as an alternative to IM-DD scheme highlighting the dispersion free transmission context [5].

2. The DSBSC method

In this paper we investigate the microwave frequency standard fiber transmission architecture based on Double Sideband Suppressed Carrier – DSB-SC modulation format. 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. The block diagram of the DSB-SC scheme is depicted in Fig. 1.

A continuous wave laser drives the Mach–Zehnder modulator, which is DC biased at $V\pi$, the voltage that shifts the phase of the optical carrier by π rad in the first arm of the modulator. At this voltage, optical phase reversal between the two arms of the interferometer takes place, so the optical output is suppressed. When the RF modulation frequency f_m is applied under such conditions, a DSB-SC optical signal is produced [6]. The spectral distance between the two optical sidebands is twice the modulating RF frequency. After passing the phase correction activators, the microwave standard carrying wavelength is transmitted to the remote end and a photodiode directly detects the RF signal at $2f_m$. A portion of the received DSB-SC modulated wavelength is routed back to the transmitter in order to perform the phase correction. At the transmitter side, a microwave frequency doubler produces a phase stable $2f_m$ replica of the frequency standard which is fed to the phase discriminator. In this way, the entire transmission path and phase correction loop operate at $2f_m$ frequency, increasing the fractional stability of the received standard and the phase discrimination sensitivity of the closed loop.

Additionally, no dispersion compensation measures are necessary, as the optical carrier is suppressed. The MZM is driven with adequate RF voltage reducing the harmonic components of the DSB-SC signal. The modulation depth, defined as $(I_{max}-I_{min})/(I_{max}+I_{min})$, where I is the light intensity, is not affected and approaches its maximum figure of 1, as I_{min} tends to zero. This is not the case in the classical IM scheme, where the magnitude of the applied RF voltage , is not sufficient to provide high modulation depth and thus achieved OSNR as it is intentionally adjusted to be as much as to operate in the linear part of the M/Z interferometer and suppress the odd harmonics. The reduced modulator's optical output power under lower RF driving signal is adequately amplified, prior to transmission.

The modulation signal V_M applied on a Mach Zehnder modulator is a sinusoidal voltage with angular frequency ω_m and amplitude V_m superimposed on a DC voltage V_B: $V_M = V_B + V_m \sin(\omega_m t)$. The output intensity as a function of the input voltage is given by [7]:

$$\frac{I_o}{AI_I} = \frac{1}{2}\left\{1 + BJ_0(C) + 2B\sum_{n=1}^{\infty} J_{2n}(C)\cos(2n\omega_m t) - 2D \sum_{n=1}^{\infty} J_{2n-1}(C)\sin((2n-1)\omega_m t)\right\} \quad (1)$$

where A is the optical insertion loss, $B=\cos(\pi V_B/V_\pi)$, $C=\pi V_m/V_\pi$, $D=\sin(\pi V_B/V_\pi)$. For DSB-SC operation, the DC bias voltage is set to $V_B=V_\pi$, eliminating the odd harmonics:

$$\frac{I_o}{AI_I} = \frac{1}{2}\left\{1 - J_0\left(\frac{\pi V_m}{V_\pi}\right) - 2\sum_{n=1}^{\infty} J_{2n}(\pi V_m/V_\pi)\cos(2n\omega_m t)\right\} \quad (2)$$

The mean optical power is determined by $J_0\left(\frac{\pi V_m}{V_\pi}\right)$ and the power of the desired $2f_m$ spectral component by $J_2(\pi V_m/V_\pi)$ while the power of the strongest fourth harmonic $4f_m$ by $J_4(\pi V_m/V_\pi)$.

The modulation amplitude V_m must be adjusted to $V_\pi/2$ in order to maximize the power of $2f_m$ optical spectral component, while keeping the fourth harmonic 12.5 dB lower. Then, the DSB-SC power at $2f_m$ is 3.5 dB weaker than f_m in the IM case, using the same $V_\pi/2$ modulation amplitude while the third harmonic in IM is only 9 dB weaker than the fundamental. An improvement of 3.5 dB is achieved in the suppression of the harmonic components when using the DSB-SC format.

In order to launch the same optical power, 3.5 dB of additional optical amplifier gain must be used in DSB-SC compared to the

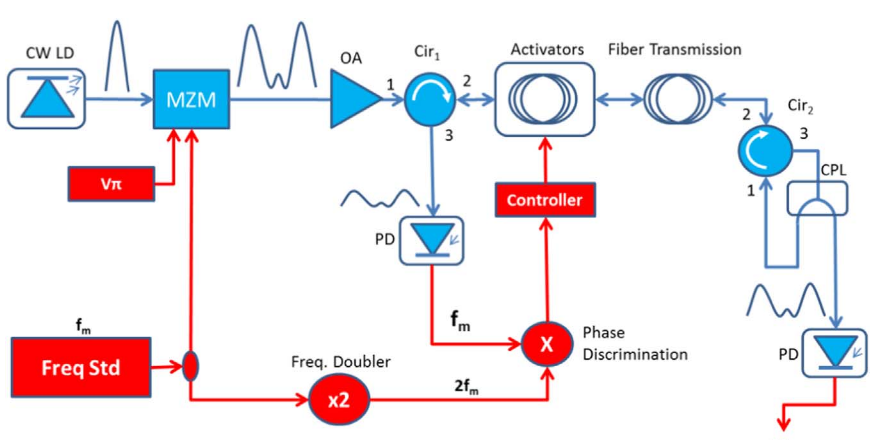

Fig. 1. DSB-SC Transmission. CW LD: Continous Wave Laser Diode, MZM: Mach Zehnder Modulator, Cir: Optical Circulator, OA: Optical Amplifier, CPL: Optical Coupler – Splitter. Red lines: Electrical signals, Blue lines: optical path. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article)

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