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A photonic BPSK modulation with 2.5 GHz RF signal from a microwave optoelectronic oscillator

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Abstract—This article presents a photonic circuit that achieves direct carrier BPSK modulation of a RF signal from an optoelectronic oscillator suitable for satellite telemetry and control. The circuit was implemented with two Mach-Zehnder optical modulators. The optical wavelength is 1550 nm. One modulator was used to construct an optoelectronic oscillator to generate a carrier with frequency equal to 2.5 GHz. The second modulator was used to perform the BPSK direct modulation of the carrier signal. A bit rate of 1 Mbps was used and an EVM of 9.6% was obtained. The diagrams of the optoelectronic circuits and the modulation measurements are displayed.

Keywords—satellite communications, digital modulation, binary phase shift keying, BPSK, optoelectronic oscillator, OEO.

I. INTRODUCTION

Nowadays, many applications implemented in electrical domains such as wireless communications, phased array radar, filters, analog-to-digital converters have been updated with microwave photonic technology [1]. Photonic technologies have many advantages over traditional electrical systems. For example, they are light weight and small, transparent to any modulation format and provide high data rates. They are also galvanically isolated and neither suffer nor induce electromagnetic interference (EMI). These advantages are desirable in satellite engineering, where the use of photonic technologies for spacecraft has attracted significant interest [2], [3].

The satellites of National Institute for Space Research (INPE) operate in the Low Earth Orbit (LEO) [4], and are used to image the Earth for deforestation control and collect data from remote stations. The communication link of such satellites operates in the S and X bands for tracking, telemetry, command (TT&C) and image transmission. In the X band, the link operates using QPSK modulation and a photonic QPSK modulator is under investigation [5]. Residual carrier Phase Modulation (PM) is the most commonly used TT&C technique to downlink and uplink with low bit rate in the S band [6]. The binary phase shift keying (BPSK) is considered for the higher bit rate uplink and moderate bit rate downlink [6].

Usually, BPSK radio frequency (RF) signals are generated in the electrical domain by using a low frequency voltage controlled oscillator (VCO). To reach the S band such a system has circuits for frequency multiplication, amplifiers and filters, resulting in a bulky, costly microwave transponder.

Taking advantage of the characteristics of photonic technology and its use in space environment, we investigate a circuit that achieves BPSK modulation directly at the carrier microwave frequency. To achieve the desired microwave carrier an optoelectronic oscillator (OEO) is used, resulting in a photonic system with reduced mass and volume.

II. BINARY PHASE SHIFT KEYING - BPSK

The BPSK is a type of suppressed carrier phase modulation, which places all of the power into the data instead of PM, which splits part of the transmitted power into data and part into a discrete carrier component [6]. In the BPSK each data bit is modulated directly onto the carrier, resulting in a spectrum in a main lobe width twice of that code rate and half the width of the residual carrier PM [6]. BPSK is suitable for spacecraft communications systems because it has the best power efficiency theoretically possible and is simple to implement in satellites [6].

In a photonic device such a Mach-Zehnder intensity modulator (MZIM), BPSK is performed taking advantage of the periodicity of its transfer function. Two equal intensity points of the transmission function separated by the modulator bias voltage have opposite optical phase [5]. The opposite optical phase results in an inverting and non-inverting modulation of the RF carrier, between 0° and 180° [7], [8].

The circuit implemented, a BPSK digital modulation, is shown in figure 1 and is similar to a microwave photonic vector modulator [5], [9].

![Fig. 1. Photonic BPSK Modulator](image-url)

The MZIM utilized is a single drive modulator and the output optical field can be expressed as [5], [10]:

\[ E_{\text{output}}(t) = A \cdot \sin(\omega_c t + \phi(t)) \]
\[ E_{\text{out}}(t) = \frac{E_0}{2} \cos \left( \pi \left[ \frac{V_d}{V_\pi} Data(t) + \frac{V_m}{V_\pi} \cos(w_{r,f} t) \right] \right) \cos(w_0 t) \] (1)

where \( Data(t) \) is the transmitted data “0” and “1” and \( V_d \) is the amplitude of the NRZ signal of \( Data(t) \), \( V_\pi \) is the MZIM half-wave voltage, \( V_m \) and \( w_{r,f} \) are the amplitude and the angular frequency of the electrical driving signal while \( E_0 \) and \( w_0 \) are the amplitude and angular frequency of the optical carrier.

From equation (1), it can be noted that switching the amplitude data signal between the values of \(-\frac{\pi}{4}\) and \(\frac{3\pi}{4}\) the BPSK modulation is performed on MZIM.

The optical signal of MZIM after being detected by a photodetector, results in a BPSK modulated microwave carrier.

III. OPTOELECTRONIC OSCILLATOR - OEO

The figure 2 shows the block diagram of OEO as originally proposed [11]. The OEO is a ring structure with an MZIM followed by a feedback loop. The length of the optical fiber provides the time delay, \( \tau \), of the feedback loop, which determines the spacing between resonant frequency components. This time delay determines also the Q factor and OEO phase noise signal output.

IV. EXPERIMENTAL RESULTS

To show the characteristic of each circuit implemented in this study, the results are divided in two parts. The two MZIMs are Lucent 2623NA LiNbO\(_3\) devices with \( V_\pi = 2.9V \). The laser is a DFB diode with a wavelength of 1550 nm and power of 17 mW. The photodetector is an InGaAs Thorlabs with a bandwidth of 5 GHz. The signals were measured with an Agilent N9020A Signal Analyser.

A. OEO

The voltage of DC bias was adjusted to \(-0.28V\) in such a way to highlight the main components from OEO. Figure 3 shows the spectrum of the OEO with spacing of 13.8 MHz between the frequencies.

![Fig. 3. OEO - Spacing between components](image)

As mentioned before, a BPF filter was not used at the OEO along the feedback loop. Without that filter the output of the OEO was a set of spectral lines separated by 13.8 MHz.

The BPF filter enables a line selection and furthermore, the best phase noise values for an OEO, for a specific feedback loop optical fiber, according to the scheme in Figure 2. The authors know that the OEO generated signal, without the BPF filter is not the lowest phase noise as could be obtained using the filter. As we are using a digital modulation with a code rate lower than 13.8 MHz, it is possible to work without that filter. Even without the BPF filter, the OEO delivered a signal with appropriated characteristics for digital modulation and the objective of this paper.

B. BPSK - Combined circuit

Figure 4 shows the circuit combining a BPSK modulator and an OEO with only one laser source. The OEO was performed with a power splitter (PS) for frequencies up to 5 GHz and two power amplifiers (PA) with bandwidth from 700 MHz to 3500 MHz, as the optical carrier was divided by optical splitter.

The binary data signal to perform the BPSK modulation, was provided by a pseudo random bit sequence (PRBS) Agilent 81130A with a length of \(2^{15} - 1\) and a code rate of 1 Mbps. The data signal was injected into the bias tee DC connector of MZIM with the voltage switching between \(-0.85V\) to \(2.5V\). Figure 5 shows the output of PD 1 with a digitally modulated frequency of 2.5 GHz. It can be seen that the several spectral components of the OEO output separated by 13.8 MHz do not interfere with the modulated signal. Afterwards they were attenuated by the optical link negative gain.
Fig. 4. System block diagram

Among the several spectral components of the OEO output, one with a frequency equal to 2.5 GHz was selected since it is on the S band. Figure 6 shows the spectrum of a BPSK signal at 2.5 GHz, where the main lobe width of 2 MHz correlates exactly to a modulation of 1 Mbps.

Fig. 5. RF carrier digitally modulated

Figure 7 shows the BPSK constellation and transmission statistics of the 2.5 GHz. Even without the BPF filter on the OEO, an Error Vector Magnitude (EVM) of 9.6% was obtained during the digital modulation. The use of EVM enables rapid verification of the Bit Error Rate (BER) performance of a satellite link during the satellite integration and test, and is particularly suitable to measurement of low bit rate satellite links [12].

The data rate of 1 Mbps to perform the BPSK modulation was increased to 2.5 Mbps and was limited by the frequency response of the bias tee. Considering TT&C of real LEO satellites, this code rate is large enough. For example, the data rate of the China-Brazil Earth Resources Satellite (CBERS) is 16 kbps and the AMAZONIA 1 is 640 kbps.

V. CONCLUSIONS

This study presents a direct digital modulation at the carrier microwave frequency based on an optoelectronic oscillator and a photonic vector modulator suitable for TT&C of LEO satellites. A set of two Mach-Zehnder optical modulators, one to perform the OEO RF signal and other to directly digital modulate the microwave carrier with a unique laser source operating at 1550 nm were used. BPSK digital modulation was experimentally demonstrated with a carrier of 2.5 GHz from the OEO and with a data rate of 1 Mbps, an EVM of 9.6% was obtained.

The signal generation and the digital modulation was achieved directly at the microwave frequency by using an OEO with the photonic BPSK modulator. Therefore the VCO low frequency reference is not needed.

The results described in this paper enable one to see microwave photonics as key technology for near future satellite developments. The authors believe that future work will be
related to integration and reliability of a digital photonic system as a satellite payload, thereby enabling enhanced functionalities.

Future work is ongoing to improve the EVM and phase noise OEO output signal.

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