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300 Mbps Photonic QPSK Modulator for Space Applications

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Abstract—This paper addresses the evolution of the photonic QPSK modulator setup previously reported. This second generation setup used two laser sources and the bias tee was replaced by a power combiner. As a result, the second setup enables one to reach higher data rates with better stability and modulated signal quality. The improved setup initially achieved a data rate of 50 Mbps in a QPSK scheme with an EVM of 8\%. Using a root-raised-cosine filter, it was possible to reduce the EVM to 4.5\%. After the EVM analysis, the modulated signal was demodulated through an actual satellite receiver. Using the demodulator, it was possible to measure the BER and verify if the incoming signal was modulated in the correct order. The QPSK modulator achieved finally a bit rate of 300 Mbps. The degradation analysis of the modulator with QPSK modulation and bit rate of 100 Mbps was 0.06 dB. In this case the values of $E_b/N_0$ and BER were 11.36 dB and $10^{-7}$. The obtained results are a consequence of the photonic technology bandwidth and the improvement made in the input and bias circuit.

1. INTRODUCTION

Currently, traditional equipment for LEO satellites such as transponders and data transmitters employs digital modulation. The carrier modulation employs in-phase (I) and quadrature-phase (Q) processing to achieve M-ary phase shift keying (M-PSK). To reach a specific communication band, such equipment could have microwave circuits for frequency multiplication, amplifiers and filters. As a result these systems are complicated, bulky and costly.

Due to the advantage of photonic technology and its use in space environment \cite{1, 2}, a photonic QPSK modulator have been demonstrated \cite{3}. In a previous study a binary phase shift keying (BPSK) and quadrature phase shift keying (QPSK) were demonstrated at a carrier frequency of 2 GHz. The modulator reached a bit rate of 2 Mbps and had an EVM of 26\% with instabilities in its constellation. The major drawbacks of this approach were: firstly, the bandwidth of the digital signal was limited due to the bias tee connected to the Mach-Zehnder modulator, secondly, the high insertion loss of one modulator and thirdly, the fact that the orthogonality of the optical signal has to be imposed through the optical fiber path.

In order to improve the first QPSK setup and circumvent the drawbacks, a diagram using different components was implemented. Thus, this study presents several improvements over the previous photonic QPSK modulator in order to achieve higher data rates, provides greater RF operation flexibility while remaining light weight and small in size. A detailed description of this setup was previously reported \cite{4}.

2. SYSTEM DESCRIPTION

The approach implemented to improve the first QPSK used two laser sources. Figure 1 shows the block diagram of the implemented setup.

The microwave signal was split by a 90 degree hybrid to generate the $\cos(\omega t)$ and $\sin(\omega t)$ components. The binary data signals, I and Q, were provided by a pseudo random bit sequence (PRBS). The bias tee was replaced by a power combiner and a new bias tee was connected between the power combiner and the optical modulators. Each RF component, $\cos(\omega t)$ and $\sin(\omega t)$, were combined with the data signals, I and Q, by the power combiner. Each power combiner drive an Mach-Zehnder modulator (MZM1 and MZM2) whose generates the BPSK modulation. The output from each BPSK modulator was combined through an optical coupler and then inserted on a photo detector, resulting in a QPSK modulated signal at the microwave frequency.

The combination of two optical signals from different optical modulators can be performed in different approaches. It can be performed with one or two laser sources and/or with one or two photodetectors. If only one laser source and one photodetector are employed, there must be an output phase control to combine the optical signals \cite{5}. This phase control is responsible for making the optical signals mutually orthogonal. With the use of two laser sources, one for each modulator, a similar situation of orthogonality can be obtained \cite{5}. For this, the laser sources may not be
coherent with each other. Thus, the optical signals were combined through an optical coupler, without requiring phase control. The use of the bias tee was necessary to control an unmodulated peak which appears in the modulated signal. It’s use will be explained in more detail in the following section.

3. EXPERIMENTAL RESULTS

In order to verify the proposed scheme, the MZM 1 and MZM 2 were driven by the laser sources in CW mode with a wavelength equal to 1550 nm and output power of 8 mW and 11 mW respectively. The MZMs are a Lucent 2623NA LiNbO3 devices. The two different optical power was due to the modulators insertion loss differences. The microwave carrier had a frequency of 2 GHz and was used two equipment to inject the digital signals. One was the Agilent 81130A with frequency up to 300 MHz and PRBS length up to $2^{15} - 1$. The other was a Rohde & Schwarz SMBV100A with an I/Q frequency bandwidth up to 120 MHz and a PRBS length up to $2^{23} - 1$. Using the SMBV100A it was possible to implement the Root Raised Cosine filter (RRC) at the baseband signals with different roll-off factor (RoF) values. The photodetector used was a Thorlabs InGaAs 5 GHz photodiode.

In the initial measurements the data rate was gradually increased in order to verify the system response. It was observed that as the data rate was increased, the modulated signal decreased and became distorted with an unmodulated peak appearing in the modulated signal. To solve this problem a bias tee was connected between the power combiner and the MZM. It was observed that a bias voltage adjustment could restore the modulated signal output. Thus, for each data rate value the bias level was adjusted and consequently, the modulated signal was recovered. The use of this bias tee permitted control of the unmodulated peak and consequently suppressed the residual carrier.

Figure 2 shows the QPSK signal spectrum with a modulation of 50 Mbps and a main lobe width of 50 MHz and the respective constellation diagrams and transmission statistics measured with the Rohde & Schwarz FSV40 Signal and Spectrum Analyzer.

As the bandwidth of the Agilent generator is larger than the Rohde & Schwarz generator, the modulated signal with data provided by the first will show more spectral side lobes. This can be noted by comparing Figure 2(a) with 2(c). After the all improvement in the QPSK setup was possible to reduce the EVM from 26% to 8%.

As the second generator was capable of implementing the RRC, the spectrum measurements were carried out with a roll-off factor of 0.35 and 0.5. Thus for a QPSK modulation of 50 Mbps, the bandwidth is 33.75 MHz and 37.5 MHz respectively. Figure 3 shows the obtained spectrum with the mentioned roll-off factors and the corresponding constellation diagram and transmission statistics for a modulation of 50 Mbps. Note that the bandwidth with RoF of 0.35 and 0.5 are 33.75 MHz and 37.5 MHz respectively as well the EVM was reduced to 4.5%.

With the proposed setup it was possible to achieve high data rates. All spectra were obtained without a residual carrier which was suppressed through the adjustment of the bias level of each
Figure 2: Measurements obtained with a QPSK modulation. (a) QPSK spectrum with Agilent generator. (b) QPSK constellation. (c) QPSK spectrum with Rohde & Schwarz generator. (d) QPSK constellation.

MZM. A data rate higher than 50 Mbps was not possible due to the limitation of the analytical equipment. In order to verify the modulator degradation and increase the data rate, a demodulation setup which will be explained in the next section was implemented.

4. DEGRATION ANALYSIS

A digital communication system can suffer a loss in the signal-to-noise ratio or $E_b/N_0$ ($E_b$ is the transmitted signal energy per bit and $N_0$ is a noise spectral density of an additive white Gaussian channel (AWGN)) due to the decrease of the received signal power or a noise power increase [6]. Such a loss in the signal-to-noise ratio results in error-performance degradation. The main idea of this analysis is to verify the modulator performance over an AWGN channel which allows one to know the BER at specific values of $E_b/N_0$. For this measurement one will use a demodulator and a noise source in order to verify the BER.

The complete setup implemented after the modulation circuit is shown in Figure 4. The microwave signal at the output of the photodetector was amplified through an LNA. The amplified signal was divided by a power splitter (PS) in order to measure the modulated signal with the signal analyzer. The other component is down-converted through a mixer with a local oscillator (LO) of 2770 MHz, which generated a beat modulated frequency of 720 MHz. To avoid unwanted frequency components from the mixer a BPF filter was used. The filtered signal was amplified due to the losses from the downconverter.

The demodulator is an actual satellite receiver from Zodiac Data Systems model Cortex HDR XXL capable of demodulating a data rate up to 400 Mbps at an intermediate frequency (IF) of 720 MHz. The Cortex also has a modulator board for test purposes. This modulator is capable of generating a noise source with a tunable amplitude level, which was used to generate noise for the modulated signal. Thus, an AWGN from the modulator board was added to the signal by
a power combiner. The resulting and final down-converted signal was injected into the IF of the demodulator.

In order to verify if the PRBS signal was correctly modulated, the received signal was compared with the internal PRBS of the demodulator. The measurements were carried out using a PRBS length of $2^{15} - 1$ or $2^{23} - 1$ depending on the generator used. As the PRBS was correctly modulated the value of BER is zero. Although the EVM and the constellation measurement were correct, it was not possible to assure that the analyzed bit was in the correct order. It is a qualitative metric.

The bit rate was increased up to 300 Mbps with the Agilent generator while with the Rohde & Schwarz generator the bit rate was increased to 100 Mbps. Figure 5 shows a modulation of 100 Mbps and Figure 6 a modulation of 300 Mbps.

Comparing the Figures 5 and 6 it is possible to note that the IF level and the $E_b/N_0$ had different values. For bit rate above 100 Mbps, the IF level began to fall as well as the $E_b/N_0$. Using an oscilloscope, it was observed that the digital signal above this bit rate began to distort...
and the voltage level began to fall. For bit rates up to 100 Mbps, the IF level remains practically the same. This is the reason for the degradation analysis was measured for a bit rate of 100 Mbps. This behavior was observed with the Rohde & Schwarz generator were the digital signal began to distort with a bit rate above 60 Mbps.
To start the degradation analysis, the noise source level was increased step by step in order to see the BER for specific values of $E_b/N_0$. For example, for an $E_b/N_0 = 10.5$ dB the theoretical BER is $1.10^{-6}$ in a QPSK modulation. Evidently, a real system will show a higher BER than the theoretical BER for the same $E_b/N_0$. The obtained BER value is converted to dB and subtracted from the corresponding $E_b/N_0$. The result of this difference is the degradation of the system for a specific BER.

Thus, for $E_b/N_0 = 11.3$ theoretical BER is $1.10^{-7}$ while the measured BER was $1.25206 \times 10^{-7}$. This measured BER corresponds to a $E_b/N_0 = 11.24$. Hence, the degradation is $11.3 - 11.24 = 0.06$ dB. This result indicates that the transmitter has to provide an $E_b/N_0 = 11.36$ dB in order to meet the same BER of $1 \times 10^{-7}$. This measure was made in 6 points of the BER curve. Figure 7 shows the theoretical BER curve compared with the measured values.

As one can see, Figure 7 shows that the theoretical curve is very close to the BER measurements. Thus, it is possible to conclude that the modulator has a performance curve close to ideal. This is a consequence of photonic technology and the improvement made in the circuit using the carrier suppression approach by the bias tee.

![Figure 7: Theoretical and measured BER values.](image)

5. CONCLUSION

This study presents an experimental analysis of a direct digital modulation at the microwave frequency using photonic technology. The use of photonic technology can greatly improve the quality of the modulated signal and enable it to increase the bandwidth of the digital signal as well as the RF carrier. These advantages are desirable in satellite engineering, particularly regarding satellite communication equipment such as transponders and the data transmitters.

The first QPSK setup was improved by using two laser sources while the bias tee was replaced by a power combiner and a new bias tee was connected between the power combiner and the optical modulators. The use of this bias tee permitted control of the unmodulated peak and consequently suppressed the residual carrier. As a result, the improved setup enables one to reach higher data rates with better stability and modulated signal quality. The first measurements achieved a data rate of 50 Mbps in a QPSK scheme with an EVM of 8%. Using an RRC filter, it was possible to reduce the EVM to 4.5%.

After the EVM analysis, the modulated signal was demodulated through an actual satellite receiver. Using the demodulator, it was possible to measure the BER and verify if the incoming signal was modulated in the correct order. The degradation determined by the modulator was measured by the demodulator. As expected, due to the use of photonic technology the QPSK modulator displayed excellent performance. The QPSK achieved a bit rate of 300 Mbps and was limited by the pattern generator bit rate upper value. The $E_b/N_0$ for a BER = $10^{-7}$ was 11.36 dB at a bit rate of 100 Mbps with QPSK modulation. As this result is very close to the theoretical value, it means that the modulator has a performance curve close to ideal. This is a consequence of the photonic technology bandwidth and the improvement made in the input and bias circuit.
If one considers data transmitter of satellites operating in LEO, mainly small satellites, the data rate achieved in this study is high enough. There is a commercial data transmitter for LEO satellites which achieves a data rate of 500 Mbps [7]. The data rate obtained in this study was limited by the PRBS generator available, as well by the actual satellite receiver. With the use of photonic technology it is possible to reach a higher throughput, which is limited by the MZM and photodetector bandwidth used.

REFERENCES