COIN – ACOFT 2007
24 – 27 June 2007, Melbourne, Australia

Low-cost RF Frequency Measurement using Photonic Approach

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***Abstract* — A technique to implement frequency measurement photonically using only low-cost DC photodetectors is proposed and a proof of concept implementation is practically demonstrated. Techniques to further reduce cost and extend bandwidth are proposed.**

I. Introduction

Frequency measurement is a critical component of a modern electronic warfare system. In a typical implementation, broadband antennas listen across the whole useable RF spectrum. A sophisticated signal processing system must then sift through the received broadband analogue RF signals and attempt to identify the signatures of potential threats. Much of this signal processing can be done in the digital domain by dividing the received signal into relatively narrow band channels, digitizing and then processing with a computer. This is the most rigorous approach to threat identification.

It is valuable, however, to have an immediate warning against some specific threats. For this purpose, instantaneous analogue frequency measurement (IFM) is preferred. Banks of IFM receivers are required to distinguish between multiple threats and thus these systems must be simple, fast and low-cost. IFM receivers can be as simple as an interferometer formed using an RF quadrature hybrid, a combiner and two mis-matched lengths of RF transmission line. The bandwidth and cost of the IFM receiver is therefore limited by the RF hybrid and combiner components.

To address these limitations, investigations into photonic IFM receivers have been conducted[x]. Optical splitters, combiners and delay lines are exceptionally broadband and very low-cost. Unfortunately, to utilize optical fibre systems, high-quality (and generally expensive) optical modulators and photodetectors must be used.

Broadband photodetectors are a major factor determining the cost of optical fibre systems. They are critically sensitive to bias conditions and are thus vulnerable to electronic attack. A photonic system with multiple IFM receivers could require a separate photodetector for each IFM. The cost of multiple *broadband* photodetectors would be prohibitive.

In this paper we explore a frequency measurement system where frequency detection is achieved via a DC measurement. This eliminates the need for broadband photodetectors and hence renders banks of multiple such systems viable. Section II presents the general concept and basic theory, Section III presents a proof of concept implementation and Section IV presents results obtained using this system. Possible improvements are discussed in Section V.

II. Theory

In this Section we propose a configuration that will produce a DC signal that varies with signal frequency. The general schematic of the proposed system is presented in Figure 1. This procedure resembles photonic mixing [1,2].

Mathematically, the process can be described as follows. The carrier tone is

$$E(t) = E_0 e^{\omega_0 t}$$

where E_0 and ω_0 are the amplitude and frequency of the carrier signal respectively. This carrier is modulated by the signal

$$v_{in}(t) = V_0 \sin \omega t$$

where V_0 and ω are the signal amplitude and frequency. The modulated carrier

$$E(t) = E_0 V_0 e^{\omega_o t} \sin \omega t$$

is delayed by τ, resulting in

$$E(t) = E_0 V_0 e^{j\omega_0 (t-\tau)} \sin \omega(t-\tau)$$

The delayed signal is then mixed a second time producing:

$$E(t) = E_0^2 V_0 e^{j\omega_o (t-\tau)} \sin \omega(t-\tau) \sin \omega t$$

If we detect only the envelope of the signal at the output,

$$I = |E|^2 = E_0^2 V_0 \sin^2 \omega(t-\tau) \sin^2 \omega t$$

Filtering to receive only the DC component, we find

$$I_{DC} = \frac{E_0^2 V_0}{4} + \frac{E_0^2 V_0}{8} \cos 2\omega\tau$$

The received DC component has a frequency independent offset and the frequency dependant level of interest.

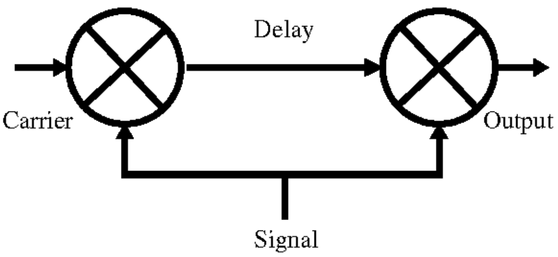

Fig. 1. Diagram of basic sysem

ISBN 978-0-9775657-3-3

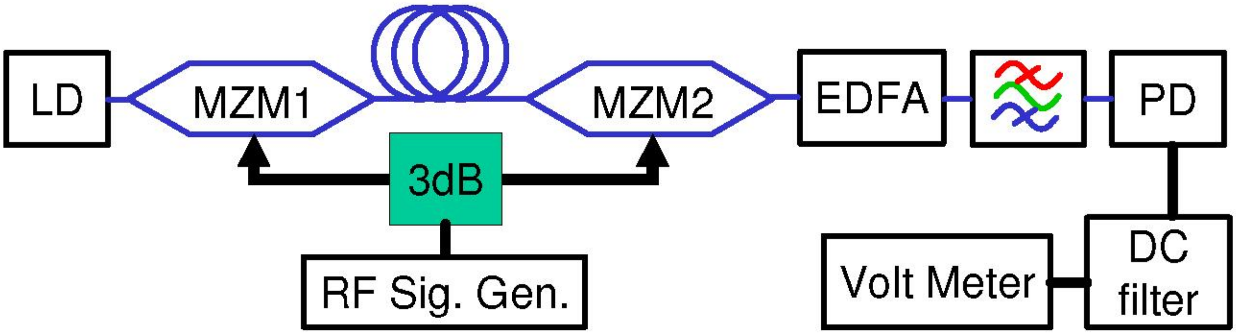

Fig. 2. Photonic configuration of frequency measurement system. LD=Laser Diode; MZM = Mach-Zehnder Modulator; EDFA = Erbium Doped Fibre Amplifier; PD= Photodetector.

III. Photonic Implementation

Figure 2 presents a proof of concept photonic implementation of the system depicted in Figure 1. An optical carrier was provided by a laser diode. This was then mixed with the signal to be measured using a Mach-Zehnder optical modulator. The modulated signal was delayed using a length of optical fibre. The delayed signal was again modulated and the result was amplified using an Erbium Doped Fibre Amplifier and filtered to remove unwanted amplified spontaneous emission. The envelope of the signal was detected using a low frequency photodetector. The electrical output was filtered to isolate the DC component and recorded using a volt meter.

In the small signal approximation a modulator response can be written

$$I(t) = \frac{I_0}{2}\left[1+\sin\left(\frac{V(t)}{V_\pi}\pi\right)\right] \approx \frac{I_0}{2}\left[1+\frac{V(t)}{V_\pi}\pi\right].$$

If the mixers in Section II are replaced with modulators, then the DC photocurrent measured at the output will be

$$I_{DC} = \frac{I_0}{4}\left[1+\left(\frac{V_0}{V_\pi}\pi\right)^2 \cos\omega\tau\right].$$

This consists of a DC offset, equal to the optical power received when no signal is present, plus the desired frequency dependant component. It can be seen that the amplitude of the frequency dependant component will be proportional to the signal power to be measured.

Figure 3 presents the anticipated DC component for a signal where $V_0=0.1V_\pi$, and the time delay ($\tau=2\pi f n_o L/c$) is caused by optical fibre with L=2.35km and n_o=1.5.

Fortunately it is possible to eliminate the DC offset by adjusting the bias of the second modulator to negative bias. This will invert the oscillating frequency dependant component, but will leave the DC offset unchanged. Hence detecting the difference between the positive and negative biased signals will yield only the frequency dependant component.

IV. Proof of Concept Results

The system depicted in Figure 2 was implemented practically. The input signal was provided with an RF signal generator. The DC output at the voltmeter was measured as a function of input RF frequency. The laser power was set to 5.4dBm and the EDFA gain was maximized. An AWG with channel width of 0.8nm was used as the optical filter. RF Signal powers of 10dBm and 13dBm were input. Separate measurements were taken with the second modulator biased at positive and negative quadratures.

Figure 4 presents the measured results obtained for this system along with the predicted response. Excellent agreement is evident. The DC level measured at the output can clearly be seen to vary sinusoidal as the input frequency is varied. The response with positive and negative bias are clearly complimentary.

Figure 5 presents the measured frequency obtained by taking the arcsin of the measured result. The implied frequency clearly follows the correct trend.

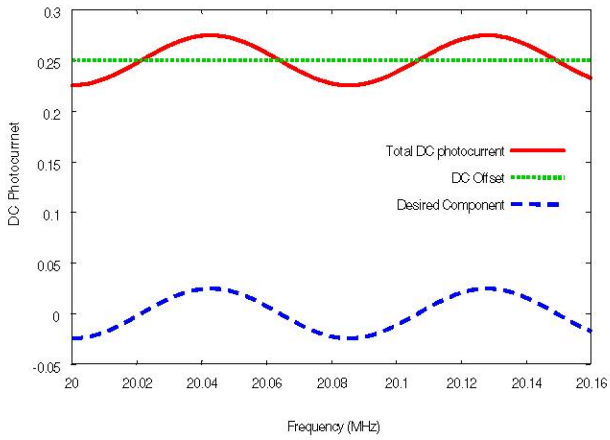

Fig. 2. Predicted Optical Response for signal amplitude of $0.1V_\pi$. DC offset and frequency dependant component depicted separately.

V. Discussion

The Results of Figure 4 clearly show the expected sinusoidal behaviour predicted in Section III. The complimentary measurements achieved using positive and negative bias should enable balanced detection. Rigorous implementation of balanced detection (with DC detectors) should provide significant noise reduction and enhanced sensitivity. These complimentary measurements could be achieved simultaneously using a balanced modulator at the output, making the measurement more instantaneous.

To increase the operation frequency, the optical fibre length must be reduced. The current system has a free spectral range of approximately 50kHz. To increase this to 5GHz would require reduction of the fibre length from 2.35km to 2.35cm. Integrated optics would clearly be an option.

It should be noted that in its current implementation, the signal amplitude cannot be isolated from the frequency. To isolate these two unknowns, two orthogonal measurements are required. One possibility would be to arrange for both sin(ωτ) and cos(ωτ) DC responses to be available at the output. This could be achieved using an quadrature hybrid phase shifter. Investigation of the combination of this current technique with a previously demonstrated photonic hybrid coupler [5] is currently underway.

Finally, requiring the RF signal at both ends of the optical fibre delay may not be practical. In fact, it would be desireable to modulate only once. This could be achieved by simultaneously modulating two different optical wavelengths simultaneously and then using a nonlinear optical component to mix the two signals[6]. We are currently seeking suitable nonlinear optical components to attempt this experiment.

V. Conclusion

We have proposed and demonstrated a simple technique by which photonic frequency measurement can be achieved using low-cost, DC photodetectors. This technique is amenable to balanced detection to eliminate the DC offset and background noise. Investigations are currently underway to improve the frequency response, reduce the component count and enhance the system sensitivity and accuracy.

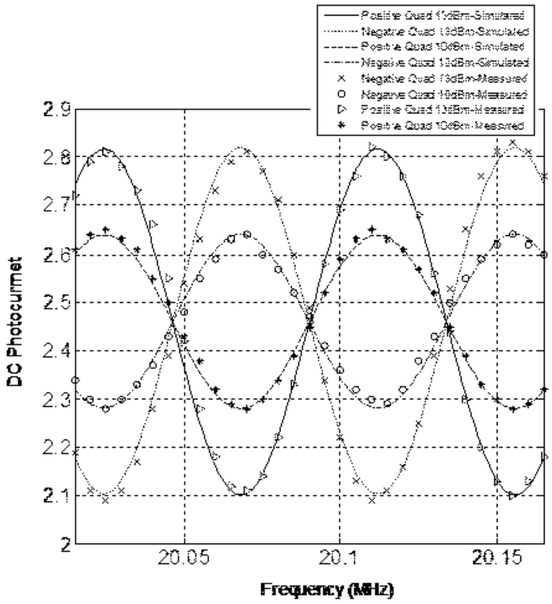

Fig. 4 Measured DC component at the output of the photonic system. Measurements were taken with input RF powers of 10dBm and 13dBm and with the MZM2 with both positive and negative bias.

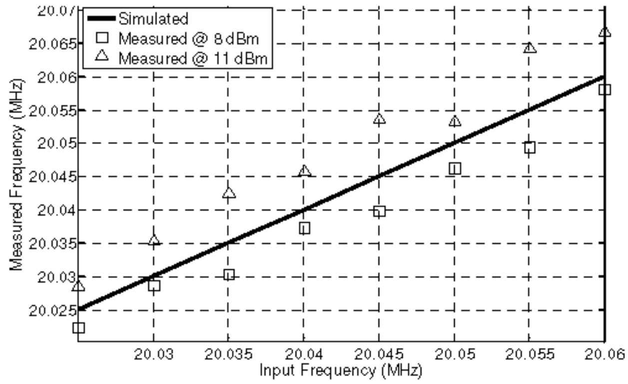

Fig. 5. Implied freuqency measurement extracted from Figure 4.

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