Opto-electronic cross-phase tuneable system based on cascaded intensity modulators

Marc Sans, Cyril Renaud and John E. Mitchell
Department of Electronic and Electrical Engineering
University College London
London, UK
m.sans@ucl.ac.uk, c.renaud@ucl.ac.uk, j.mitchell@ucl.ac.uk

Abstract— **We demonstrate a dual-output microwave photonic system that allows 360-degree per element up-converted phase adjustment with potential applicability in phased array systems. Two self-correlated Ku-band carriers are generated in the optical domain through beating by means of concatenated intensity modulators fed by lower frequency electrical sources, where the phase-tuning originates. The system shows high correlation along the full phase sweep between its outputs, which are characterized individually in terms of phase noise and spectral stability.**

Keywords—beamforming; microwave photonics; phased-array systems

I. INTRODUCTION

Since the first deployments of phased array antenna (PAA) systems based on distributed radar to detect intrusive aircrafts during the World War II, the PAA field has evolved technologically and expanded in terms of applications vastly [1-7]. Sectors such as telecommunications (ground and satellite), astronomy, health care and automotive have adopted phased array antenna technology - based on analogue and/or digital means - for a wide range of frequency bands and user case scenarios.

Nowadays, beamforming systems are used not only to augment antenna's directivity and steer its main lobe, but also for more complex capabilities such as beam nulling (interference avoidance) or multi-beam services [8]. In order to accomplish these functions, each antenna element requires a synchronised feeding signal with a different amplitude and temporal deviations (weighting). For the later, phase shifting (PS) elements are traditionally used as an approximation to time delay for narrowband systems, in order to reduce system's complexity and will also be assumed in this work.

Particularly, for next generation wireless communications systems, an ever increasing capacity demand ultimately translates into better frequency use and/or larger bandwidth allocation. Due to spectrum congestion below 6 GHz bands, upper spectrum regions such as: millimetre-wave (30-300 GHz), terahertz (0.3-3 THz) and free-space optical have been receiving increased interest over the last years for future wireless communication systems [9-12]. Usage of those bands imply higher path loss and absorption where line-of-sight (LoS) traditionally becomes a must to account for a positive link margin. PAA systems with beamforming capabilities are a potential solution to aforementioned challenges.

Microwave photonics aims to translate the inherent benefits of optical systems (mostly, large bandwidth and low distribution losses) into the microwave domain. Several functionalities such as: signal generation, processing, filtering and sampling have been demonstrated already [13-15]. A variety of work has been carried out for beamforming solutions with further benefits such as broad tuneability and squint free steering for wideband signals. Technologies such as: voltage-controlled phase-shifters, fibre based grating structures with tuneable lasers, liquid-crystal systems or optical ring resonators have been demonstrated [16-19]. Furthermore, those systems which can potentially be integrated on-chip are of especial interest for market feasibility due to a promise in reduction of: size, weight, power consumption and cost.

We present a system which accomplishes microwave photonic signal generation while up-converting a low-frequency phase tuneable signal to a higher-frequency band. The system benefits from lack of use of high frequency phase shifting elements and provides high frequency tuneability. This paper is organized as follows: in Section I we have introduced the topic and need; Section II presents the microwave photonic cross-phase tuneable concept including a simulation scenario; next, in Section III we discuss the experimental setup proving the concept; finally Section IV concludes our work.

II. CONCEPT PROPOSAL

Frequency translation through mixing is a well-known method used across the radio community to minimize the need of higher frequency components for technological and cost reasons. Still in the analogue domain, the concept of intermediate frequency beamforming is also employed. We propose the use of up/down-conversion within a microwave photonics system for phase distributed systems targeted at 5G delivery networks [20].
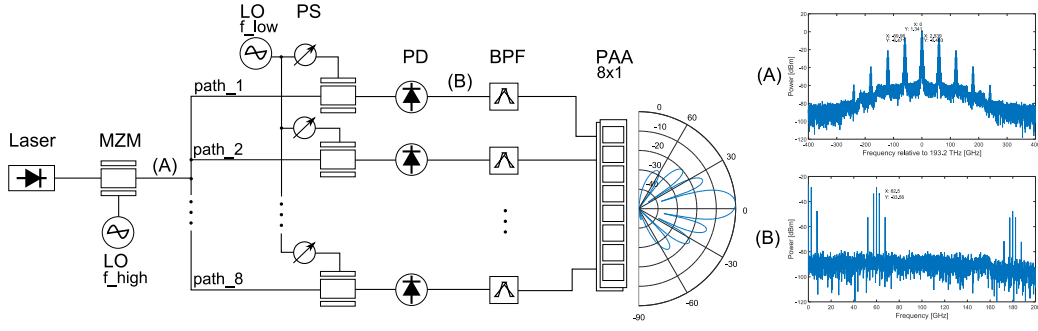
Fig. 1. Simulation diagram

In our conceptual system (Fig. 1), we generate several correlated optical tones with a frequency spacing of *f_high* using a single laser source and a high frequency intensity modulator. The output signal is then equally split across several paths. Each of the outputs is then individually fed onto a lower frequency intensity modulator. At the same time, those lower frequency intensity modulators are fed with a phase-adjustable *f_low* tone. The distribution of the low frequency sources is synchronized. A photodiode (PD) follows each arm and down-converts to the electrical domain all beating tones originating from the concatenated optical modulations. A band-pass filter (BPF) per arm is included after each photodiode to select the frequency of interest, *f_final = f_high + f_low*.

The proposed concept for *λ = 1550 nm* with local oscillator (LO) frequencies satisfying a radiation (*f_final*) frequency in the Ku, Ka and millimetre-wave (60 GHz) bands has been simulated (notice the change in centre frequency of the BPF) showing a linear phase response and broad frequency tuneability. VPI Transmission Maker has been used with single electrode Mach-Zehnder Modulators (MZMs) as amplitude modulators. From the simulation, we obtain the optimum DC bias operation points of the MZMs (aka, maximal accumulated electrical power at the output of the system) as shown in Fig. 2. The obtained output signals are interfaced with Matlab to illustrate the beamforming concept in an 8x1 uniform linear array (see Fig. 3). The element pattern is approximated by a cosine function (factor of 1.35), and the spacing between elements is set to *λ*/2 (different for aforementioned *f_final*). No amplitude tapering is used.
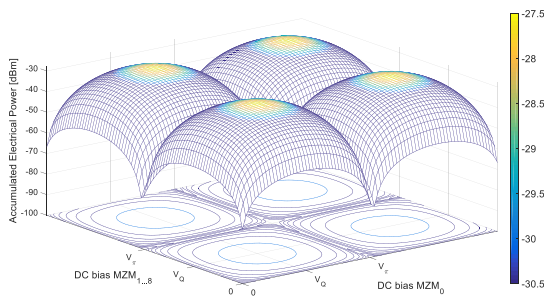
III. LABORATORY DEMONSTRATOR

A proof of concept of the cross-phase tuneable system based on cascaded single-arm Mach-Zehnder Modulators is illustrated in Fig. 4. Relevant power measurements (in parentheses) across the setup are included there for better comprehension. The objective of the setup is to up-convert the phase information of two 3 GHz sources (one source per arm) onto 13.5 GHz tones such as the phase-induced difference between them is kept correlated.

First, 3 tones at 1554 nm spaced 10.5 GHz are generated using a 40 Gbps MZM (DC bias adjusted such carrier-to-sidebands power difference is minimized) with a 10 KHz intrinsic linewidth external cavity laser. The polarization state is manually adjusted prior to each MZM through polarization controllers (PC) for polarization alignment. The 40 Gbps MZM output tones are then amplified using a double stage erbium doped fibre amplifier (EDFA: *Noise figure = 6.25 dB*) to combat power losses across the setup. The optically amplified signal is then routed onto a 4 nm bandwidth tuneable optical bandpass filter to reduce the Amplified Spontaneous Emission (ASE) noise. Then, the optical signal is equally split and used as the input to 10 Gbps MZMs per arm (both with similar specifications). Each 10 Gbps MZM is driven through a different signal generator (*f=3GHz, P.out = 10 dBm*) and referenced using a 10 MHz internal local oscillator. These signal generators provide the adjustment of phase and amplitude individually onto each arm. The 10 Gbps modulators are biased at their quadrature points as per simulation results shown in previous section.

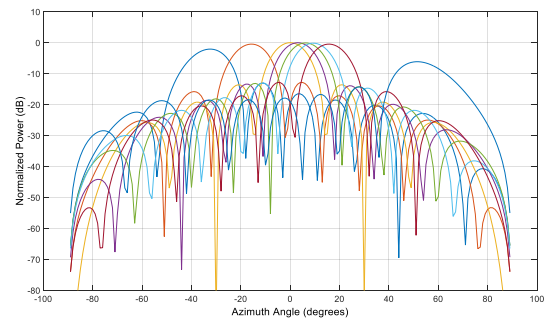Fig. 2. MZM operation points (DC bias)

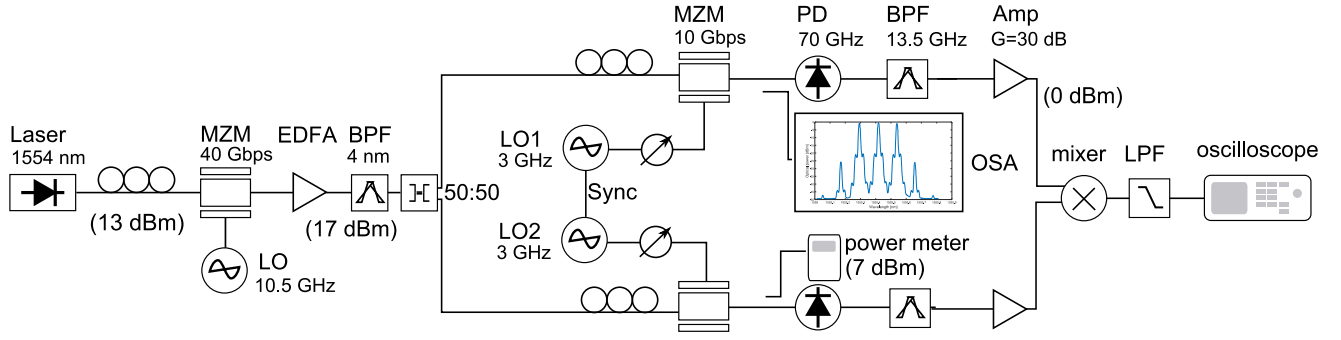Fig. 3. Far field radiation pattern for -30 to +50 degrees scan

Fig. 4. Laboratory diagram

The optical spectrum measurements are obtained with a 0.01 nm resolution optical spectrum analyser (OSA). Before each photodiode, 3 higher peaks (10.5 GHz spaced) 0 dBm are amplitude modulated (3 GHz) resulting on -20 dBm tones. The noise floor around the band of interest after optical amplification is -50 dBm. Optical average power prior to each photodiode is kept around 7 dBm.

A pair of 70 GHz photodiodes are used to down-convert all beating tones. Afterwards, a band-pass filter (BPF) (*fc = 13.5 GHz*, *BW_3dB = 140 MHz*) is used to select those of interest, and a double-amplification stage (total gain ~30 dB) for each arm is used to provide sufficient power to the phase-detector. The phase-detector is composed of a wideband double-balanced mixer followed by a low-pass filter (LPF) (*DC-780 MHz*). Its DC output will be proportional to the phase-difference between the two input ports assuming amplitude stability onto the input ports. Although mixer's recommended operation point is an LO input of 13 dBm, a lower power input signal has been observed to perform correctly after characterization at several input levels.

Finally, the filtered output of the mixer is connected to a digital communications analyser for a DC voltage measurement. In order to measure the phase-response, one signal generator is phase-swept across its entire range (-π to +π) while subsequent voltage average measurement from the analyser are read out. The measurement is composed of 126 points captured over a period of 12 seconds.
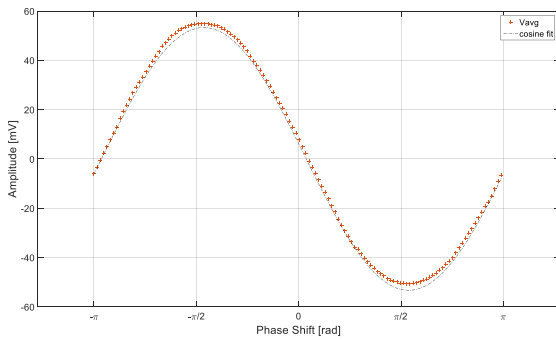
The response of the phase-measurement system for a 3 GHz to 13.5 GHz optically up-converted tone is shown in Fig. 5. The characterisation shows a well-balanced function (symmetry across X-axis), a voltage peak to peak of 105 mV and a residual DC offset of 2 mV. The graph is matched with a cosine fit showing an accurate phase-difference predictability.

As shown in Fig. 6, selected microwave photonic generation and transport methods enable high frequency stability onto the 13.5 GHz tones regardless of the observed laser source drift over a 3 hours waterfall measurement. Phase noise measurements were also conducted onto the RF sources and after each 13.5 GHz band-pass filter (see Fig. 7). As expected, the output phase noise slightly degrades from the cumulated original sources. Besides thermal and vibration contributions, we also attribute that increase and peaks to imperfections onto optical components and the FC/PC fibre adapters used.
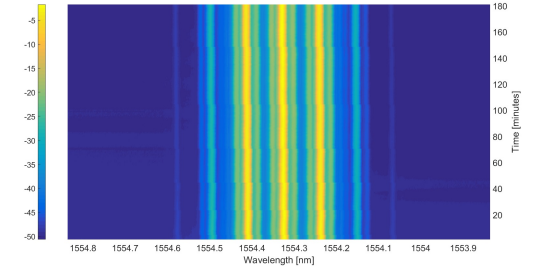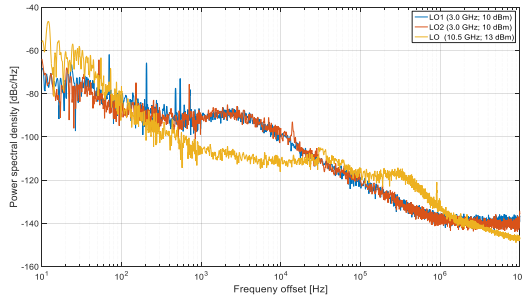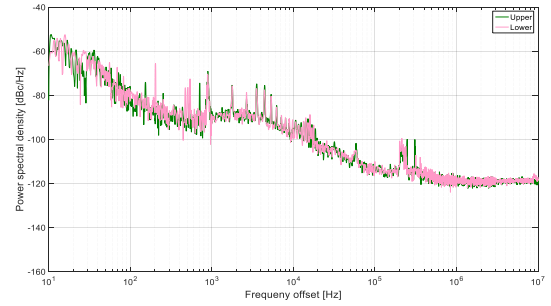

a) Spectrogram prior photodiode
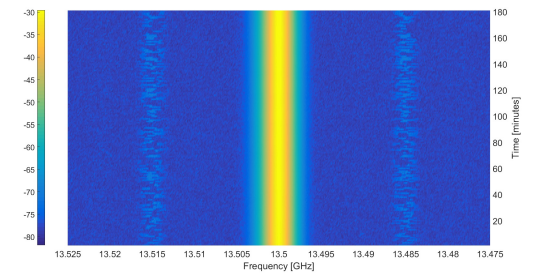
b) Spectrogram after photodiode

Fig. 6. Stability measurement

Fig. 5. Response of phase-measurement setup and cosine fit

a) Signal generators

b) After band-pass filters

Fig. 7. Single side-band phase noise measurement

IV. CONCLUSIONS

We have presented an opto-electronic beamforming concept with up-conversion phase stage using cascaded optical intensity modulators. The system avoids the use of high frequency phase shifters and enables high frequency tuneability - if tuneable band pass filters at each photodetector output, and careful selection of modulated tones are included.

The proof of concept shows a reliable frequency and phase stability, despite the simplicity of the setup (where any feedback or control loops are utilized) which have been observed over long duration spectral measurements and phase noise measurements. Anticipated power loss across the system mostly due to: conversion stages, optical modulators insertion losses and undesired beating tones have been compensated by use of optical (EDFA) and electrical amplifier stages.

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