Concepts for SAR Systems with Photonic Beamforming

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***Abstract*— In recent years there has been an increasing demand on Synthetic Aperture Radar (SAR) systems in terms of mapping capability and imaging performance. As a result many new techniques using digital beamforming (DBF) have been developed. These techniques include scan-on-receive (SCORE), dispersive SAR, multi-beam SCORE, and f-scan mode. However, DBF has several disadvantages and as an alternative, photonic beamforming (PBF) is currently being proposed as a solution to future SAR systems. This paper gives an overview of PBF benefits and drawbacks and possible architectures with their potential application to modern SAR techniques. Ideas and plans for potential future research is discussed including a SAR ground demonstrator and performance evaluation tools for implementing MWP subsystems in SAR.**

***Keywords*— SAR, Microwave Photonics, Optical Beamforming Networks, Photonic Beamforming, SCORE, Multi-Beam SCORE, Dispersive SCORE, F-Scan**

I. Introduction

Spaceborne SAR systems have been used for decades to image the Earth and the demands on performance have continuously been increasing. The desire is to simultaneously achieve a wide swath on ground while maintaining a high spatial resolution in azimuth, so called high-resolution wide-swath (HRWS) imaging [1][2][3][4]. Using conventional SAR techniques there is a tradeoff between achieving these two requirements. A wide swath results in a low spatial resolution and conversely a high azimuth resolution results in a narrow swath [5]. To overcome this limitation several new techniques have been developed, such as scan-on-receive (SCORE) [6][7], dispersive SCORE [8][9][10], multi-beam SCORE [11][12], staggered SAR [13], and f-scan mode [14]. To facilitate these techniques digital beamforming (DBF) has become increasingly researched and implemented [9]. However, DBF comes with a number of significant drawbacks, including narrow bandwidth (BW) and beam squint [15][16], as well as a worse SWaP-C (Size, Weight, Power consumption, and Cost), high complexity, and computational load [17][18]. An alternative hardware solution that has recently become increasingly viable is the use of microwave photonics (MWP) to implement optical beamforming networks (OBFN) [19]. The concept of photonic beamforming (PBF) is illustrated in Fig. 1. Instead of directly converting the signal to the digital domain the signal is modulated on one or several optical continuous wave (CW) sources. Substantial parts of the signal processing and beamforming (BF) is subsequently performed in the optical domain.

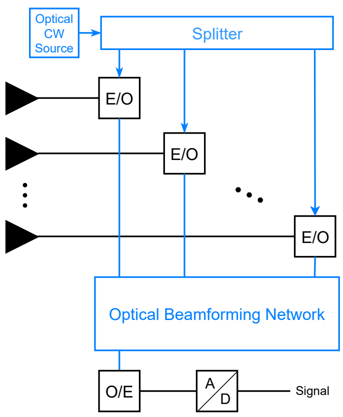

Fig. 1. Example of an OBFN using one optical CW source.

Using MWP brings many potential benefits that are currently not achievable through digital architectures [19]. Optical hardware is more lightweight than digital and RF hardware. Power consumption and computation requirements are reduces since optical hardware can operate at lower power and is an analog solution. Furtermore, using PBF enables broadband true time delay (TTD) BF without the same complexity as DBF. Finally, there is an expected reduction in complexity and cost and, as such, a solution using MWP would achieve a better SWaP-C than a digital system [17][18][20].

The aim of this paper is to give an introduction and overview of MWP and OBFN as applied to modern SAR systems and specifically discuss concepts and ideas for implementing PBF on future SAR systems. The focus will be on elevation beamforming in receive mode.

II. Introduction to Photonic Beamforming

A. Basic operation of a Microwave Photonics System

Considering Fig. 1, there are many ways to convert the RF signal to the optical domain and vice versa. Methods to modulate the RF signal on an optical carrier include, direct laser modulation, external intensity modulation, external phase modulation and polarization modulation, among others [21]. The currently most popular scheme is external intensity modulation using a Mach-Zehnder modulator (MZM)

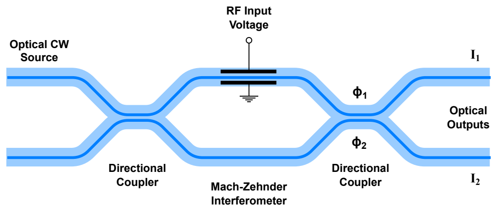

Fig. 2. Simplified diagram of an example of a Mach-Zehnder modulator.

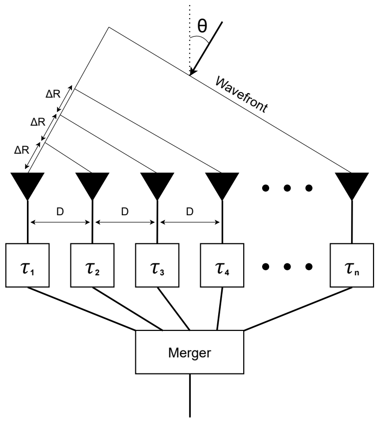

Fig. 3. Reception of a planewave signal at a linear antenna array [22].

combined with direct detection using a photodiode (PD) [17][18][21]. The basic operation of a MZM is illustrated in Fig. 2. The laser source signal is split in two, whereby one or both branches are phase modulated by the RF signal. The two branches are then combined or coupled resulting in an intensity modulation of the light. This intensity can be directly sampled with a PD to convert back into an electrical signal.

B. *True Time Delay Beamforming*

TTD means that a temporal delay is applied to each signal in an antenna array before adding them to enable beamsteering, as is illustrated in Fig. 3. Conversly, in many systems a phase shift is applied for each element to steer the beam instead. However, the phase shift needed varies with the wavelength of the incoming signal. If a broadband signal is used, the beam direction will therefore vary across the BW. This does not occur for TTD BF since it introduces the reverse phase variation over the BW. The time delay for each element in a uniform array can be described as [16]

$$\tau_n = n\frac{\Delta R}{c} = n\frac{D\arcsin(\theta)}{c}, \tag{1}$$

where c is the speed of light and the other parameters are illustrated in Fig. 3. TTD can be easily applied using OBFN. In the optical domain there are several ways to introduce group delay, a time delay of your signal. For example, using delay lines, ring resonators or dispersive elements such as fiber bragg gratings (FBG) or dispersive fibers [15][19][22].

III. Photonic Beamforming Architectures

PBF can be implemented using several different types of structures and hardware technologies. The group delay inducing elements mentioned in the Sec. II can be employed in architectures using a single or multiple lasers to perform the beamforming [15][23]. The OBFN can then easily be combined with optical frequency filter functions such as a finite impuls response (FIR) or infinite impulse response (IIR) filters. This capabillity would be useful for dispersive SCORE and f-scan as discussed in Sec. IV

A. *Single CW Source*

An example of using a single CW source to create an OBFN has already been shown in Fig. 3. In this solution all incoming RF signals are modulated on the same frequency laser. A network of ring resonators, FBGs, delay lines or dispersive fibers can then be employed to induce the correct time delay for steering the beam. An example using FBG is shown in Fig. 4a. Here, each incoming signal is passed through a distributed or linearly chirped FBG (LCFBG) to induce a group delay. The delay is determined by the optical carrier frequency through a tunable optical source. This way the beam can be steered across the target angular range by sweeping the wavelength of the tunable laser [15]. The FBGs in this example can also be exchanged for any other dispersive element using the same architecture to form a fibre-optic prism (e.g. the one presented in [19]).

Another viable single laser source solution can be seen in [17], [18], and [24]. Here a blass matrix [25] is employed to create OBFN where each node is composed of a Mach-Zehnder interferometer (MZI) and phase shifters or delay elements. If phase shifters are used the TTD property is lost and limits maximum BW.

B. *Multiple CW Sources*

Using a single CW source is not the only way to create a OBFN. Several lasers or a sliced ultrawide band source can be used to modulate the received signals. In Fig. 4b another method using FBGs is used. This time each antenna elements RF signal is modulated on separate lasers with different wavelengths [15][23]. These are then combined and passed through a tunable LCFBG to achieve different beam angles. It is also possible to use a fixed LCFBG and tunable lasers in this configuration.

In [20] we can see the same multi-laser setup used, but with the LCFBG exchanged to a MWP signal processing unit containing a programmable photonic processor that introduces the required phase shift to each optical carrier. However, in this solution the TTD BF is lost.

IV. Application to Modern SAR Techniques

A. *SCORE and Multi-Beam SCORE*

In order to improve the range resolution and improve ambiguity suppression a new concept where the beam is scanned along the swath on receive has been proposed. This improves the SNR and ambiguity suppression and allows for a wider swath. Essentially, the BFN is required to actively scan across the elevation angles corresponding to the swath on ground [6][7]. As illustrated in Sec. III this can be performed

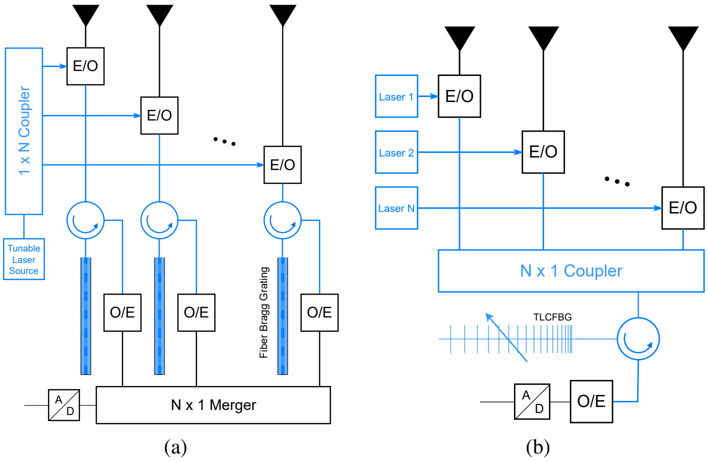

Fig. 4. Optical beamforming networks based on: (a) fiber bragg gratings (FBG) and a tunable laser; (b) a tunable chirped fiber bragg grating (TCFBG) and multiple locked lasers.

using OBFN in several ways. The network illustrated in Fig. 4a can be designed so that scanning the tunable laser corresponds to TTD in the FBGs that steer the beam along the SAR echo direction. The same effect can be achieved by actively tuning the LCFBG in Fig. 4b. Additionally, a blass matrix OBFN can be designed to produce a fan of beams that spans the swath width or the each node of the blass matrix can be tunable to produce steerable SCORE beams.

The concept of multi-beam SCORE is proposed to enable an even wider swath. In order to extend the receive time of the transmitted pulse multiple beams are used simultaneously to receive several echos in parallel. The beams each have their own set of time dependent SCORE weights and follow one echo each [10][11][12]. The usage of OBFN can be extended to facilitate several simultaneous beams. In the case when the beam is steered using a tunable laser source and FBGs as in Fig 4a this could be done by having one tunable laser per beam that scans one echo each. The same procedure is possible for the tunable LCFBG from Fig 4b. When a fan of beams is used, such as in the Blass matrix case, each beam output can be digitized separately and a time dependent selection procedure could be employed where the chosen OBFN output is changed as the echo moves accross the beams. If each node of a blass matrix is tunable, then the number of beam outputs determines how many simultaneous SCORE beams can be employed.

B. *Dispersive SCORE*

The pulse of a SAR has an extent on ground that is smaller than the swath but that may be larger than the SCORE receive beamwidth. This can result in pulse extension loss, radiometric bias, and an amplitude taper on the return spectrum. To mitigate this the method of dispersive SCORE has been proposed [8][9][10]. At any point in time during reception of the signal, frequencies from the whole chirp BW impinges on the antenna and each frequency can be shown to correspond to a specific elevation angle of arrival. This means that the instantaneous signal can be filtered into several spectral subbands, where weights for each band is applied. This type of processing is possible to combine with OBFN in the MWP domain. As an example, ring resonators can be used to create a filter for each subband as in [22], whereafter each subband is passed through a FIR filter as described in [23].

C. *F-Scan Mode*

An alternative to SCORE for achieving wide swaths is the f-scan mode [14] which offers a reduction in complexity, high SNR, and inherent sidelobe suppression. The basic principle is to exploit the beam squint phenomenon to create a frequency scanning antenna. A chirp signal is designed with a transmit period equal to the time extent of the swath on ground. Simultaneously, the frequency dependent antenna radiate the chirp across the angular extent of the swath, ensuring that the far range frequencies are transmitted first and the near range frequencies last. The consequence is that the echo window length is near instantaneous which maximises the pulse width within the duty cycle and thereby the swath width. The drawback of this method is that the effective bandwidth is now reduced to [14]

$$B_{\text{eff}} = B_{\text{chirp}} \frac{\Delta\theta_{\text{ant}}}{\Delta\theta_{\text{ant}} + |\theta_2 - \theta_1|}, \tag{2}$$

where $\Delta\theta_{\text{ant}}$ is the beamwidth of the antenna and θ_1 and θ_2 are the look angles for the near and far range. As a result of Eq. 2 the range resolution is decreased. This must be compensated for with a higher chirp bandwidth to achieve HRWS imaging. PBF would constitute a viable solution given that the relative BW remains very low despite the increase in RF BW. Using a MWP solution in both Tx and Rx would enable f-scan mode to be implemented for wide swaths while maintaining a high resolution. MWP solutions using wideband chirp signals in the higher frequency bands could therefore be investigated. To simulate reconfigurable beam squint effect an appropriate combination of phase shifters and TTD elements can be implemented in the OBFN design [22][23]. This is all realisable via photonic hardware.

V. Drawbacks and Challenges

One significant drawback of using MWP is the conversion losses in the modulation and demodulation stages. These losses can be in the order of 30 dB or higher [21]. This leads to optical amplifiers being inserted into the system to compensate for the losses. Together with high BWs, this leads to the potentially high noise (NF) figure of a MWP link which can reach up to 30dB or more [18]. This problem can be mitigated via placing the MWP subsystem after low NF RF components, e.g. a low noise amplifier (LNA). The dynamic range is directly linked to the NF and may also suffer. As such great care needs to be taken to control these performance metrics.

VI. Future Research and Conclusion

In order to realize the potential solutions discussed previously further research is required. Firstly, a rigourous performance evaluation of a spaceborne SAR system with a photonic beamformer shall be performed. This will include impacts on signal-to-noise ratio (SNR), noise-equivalent sigma-zero (NESZ), azimuth ambiguity-to-signal ratio (AASR), range ambiguity-to-signal ratio (RASR), dynamic range, NF and other system level parameters. This could additionally be complemented with investigations on reconfigurability and tunability of such a system. Previous research has shown promising results in this regard [22].

The German Aerospace Center (DLR) is currently developing a ground-based SAR demonstrator with DBF capabilities for versatile scientific use [26], [27]. The demonstrator consists of a reflector antenna with a feed array and is designed to implement the techniques suggested in [6], [7], [9], [10], [11], and [13]. Additionally, the system design is based on proposals for spaceborne SAR missions in L-band, like Tandem-L [12][28], NISAR [29], and Rose-L [30] [31]. In parallell with the DBF capabillities a PBF unit capable of being integrated into the demonstrator will be developed. This unit would verify experimentally the results of the performance estimation.

Photonic Beamforming is a promising solution to implementing SAR beamforming and modern SAR techniques, and should therefore be developed in parallel to DBF solutions, with many possible OBFN architectures candidates for implementing future HRWS SAR systems.

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