SPACEBEAM optical beamformer for SAR – A potential enabler for the SKADI mission

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ABSTRACT

Advanced SAR imaging modes benefit from the implementation of beam steering capabilities in the SAR instrument. Beam steering is typically achieved by RF analog, digital or hybrid approaches. With the latest advances of microwave photonics, specifically the photonic integrated circuit (PIC) technology, beam steering implementations in the photonics domain offer an attractive alternative. PIC technology allows frequency agnostic operation, i.e. they can be designed to work in different radio frequency bands, such as X-, Ku-, or Ka-band.
Here, an innovative radar receiver based on PIC technology will be presented. The PIC implements precise, continuous beamforming-on-receive of wideband signals from a 12 antenna elements array, synthesizing up to three simultaneous beams. The PIC also implements frequency-agnostic photonic down-conversion so that the synthesized beams can be directly digitized.
The application of the PIC technology for Ka-band frequencies is discussed such as for the Earth Explorer 11 mission proposal SKADI which is a Ka-band interferometric radar for cold environments.

INTRODUCTION

The system requirements for future spaceborne SAR instrument often require the instantaneous imaging of a wide swath at a high resolution which can be realised by advanced SAR imaging modes such as scan-on-receive (SCORE), [1].
Figure 1 illustrates the SCORE mode. On transmit a wide swath is illuminated while on receive multiple simultaneous high-gain Rx beams are steered in the fast-time domain across the swath to receive the radar echoes stemming from different transmit events. SCORE requires the implementation of fast-time domain beam steering on receive and can conveniently be implemented by an array-fed reflector configuration. Multiple independent receive channels in

elevation of a feed array can be combined via digital beamforming to synthesize the required Rx beams. However, the digital implementation of the fast-time domain beam steering requires a significant amount of system resources (especially power) because each receive channel needs to be digitized before being processed.

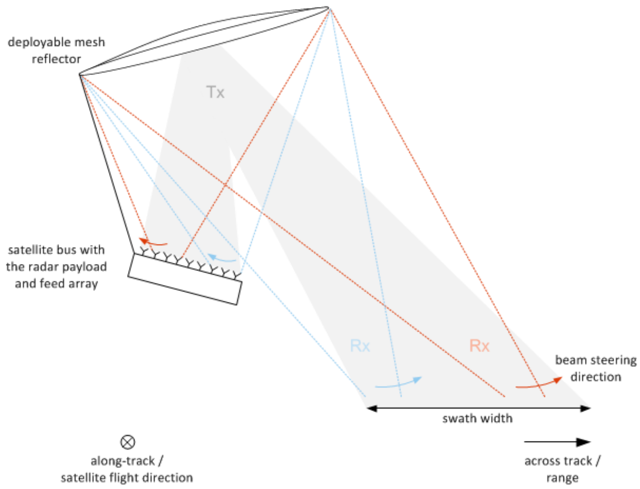


Fig. 1. Illustration of scan-on-receive (SCORE) imaging mode.

Microwave photonics, [2], provides an attractive technology option for the implementation of such beamformer. Especially photonics integrated circuit (PIC) technology promises beamformer implementation options with significantly lower size, weight and power (SWaP) compared to digital beamforming, potentially enabling the use of advanced SAR imaging modes also on compact SAR satellites.
This paper presents the specifications and preliminary design of a SCORE SAR receiver implementing a hermetically packaged hybrid InP/TriPleX™ PIC from the H2020 project SPACEBEAM. The PIC implements fast time domain beamforming on receive as well as the photonic frequency down-conversion to intermediate frequency (IF).
The paper is structures as follows: first the SPACEBEAM SAR system concept is introduced followed by a discussion of the system requirements and conceptual design of the SAR instrument. The beamformer design as well as system and beamformer performance is discussed. The contribution concludes with a discussion of the application of the PIC technology for Ka-band interferometric SAR.

SAR SYSTEM CONCEPT

This chapter introduces the system requirements and the high-level conceptual SAR instrument design. The goal of the system requirements and the conceptual design is to derive representative key functional and performance requirements for the SAR receiver front-end and the PIC.

System Requirements

Table 1 summarises the high-level SAR system requirements which were used as baseline to derive key receiver front-end and beamforming requirements.

Table 1. SPACEBEAM system requirements

Parameter	**Value**
Sensor Type	Spaceborne SAR
Orbit Height	500 km
Frequency Band	X-band
Swath Width	> 50 km
Ground Resolution	< 1.3 m × 1.3 m
Noise Equivalent Sigma Zero	< -20 dB
Ambiguity to Signal Ratio	< -20 dB
Dynamic Range	> 30 dB

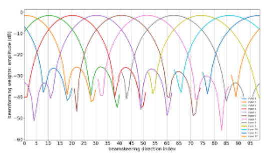
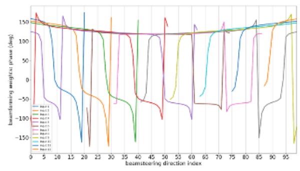
SAR System Design

The conceptual SPACEBEAM SAR system design is based on a SAR system equipped with an array-fed reflector antenna implementing the scan-on-receive imaging mode.

The reflector has a circular rim and a diameter of 2.9 m with an F/D of 0.9. The feed array consists of 12 elevation channels providing the needed elevation steering interval of up to 4.9 deg to achieve the >50 km swath width at steep incidence angles of <25 deg.

To achieve the required NESZ, a transmitter with 3 kW peak power and 11% RF duty cycle would be required. The RF bandwidth is <400 MHz at X-band.
The focus of the SPACEBEAM activity is the design of the receiver and with the PIC beamformer. The key receiver and beamformer requirements are summarised in Table 2.

Table 2. SPACEBEAM receiver and beamformer requirements

Parameter	**Value**
Receiver RF input channels	12 at X-band centre frequency
Receiver IF output channels	3 synthesised beams at 1300 MHz
RF bandwidth	< 400 MHz
RF dynamic range at receiver input	> 32.5 dB
RF power at receiver input	between -90 dBm to -57.5 dBm
Receiver noise figure	< 6 dB (goal)
RF power at PIC input	between -53.7 dBm to -21.4 dBm
Beamforming dwell time	2 to 3 µs (incl. switching time)
Beamforming weights switching time	< 300 ns / goal < 100 ns
Beamforming weights amplitude relative error	< 5%
Beamforming weights random phase error	< 10°
Beamforming weights as function of beam	 Amplitude  Phase

The receiver inputs are formed by the 12 elevation channels of the feed array. Its outputs are three synthesized beams at intermediate frequency as illustrated by the high level receiver block diagram in Figure 2.

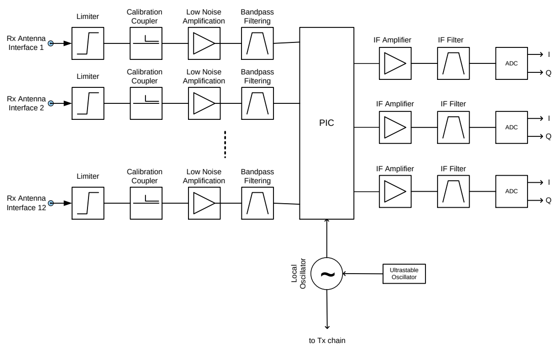


Fig. 2. SPACEBEAM receiver high level block diagram.

For the SCORE operation and fast-time domain beam steering, it is required that an Rx beam remains on a position for about 2-3 µs before being moved ahead. For this scenario, 50 Rx beams are required to cover the 50 km swath width. The required beamforming weights are shown in Table 2 and have been derived by the minimum variance distortionless response (MVDR) beamformer, Beamforming weights amplitude relative error and random phase error have been derived based on assumptions with respect to acceptable SNR losses and depointing errors. More details regarding the SPACEBEAM receiver are provided in [5].

BEAMFORMER DESIGN

The PIC beamformer is realized using a hybrid integrated photonic technology, merging InP and TriPleX™. TriPleX is a silicon nitride (Si3N4) on insulator waveguide technology developed by LioniX [3].
The PIC architecture is shown in Figure 3, where LD stands for laser diode; MZM: Mach-Zehnder Modulator; SSBF: Single-sideband filter; LSB: Lower side-band; USB: Upper side-band; SOA: Semiconductor Optical Amplifier; OBFN: Optical Beamforming Network; S-LSB and S-USB: Signal lower and upper sideband; PD: Photodiode; ADC: Analog-to-Digital Converter.

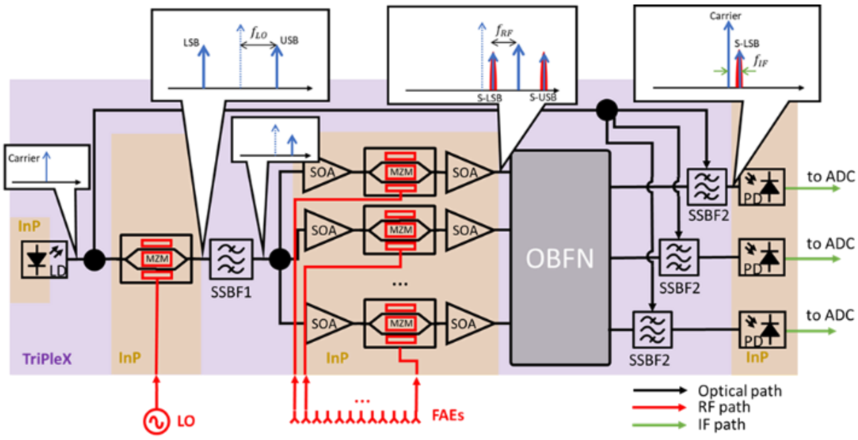
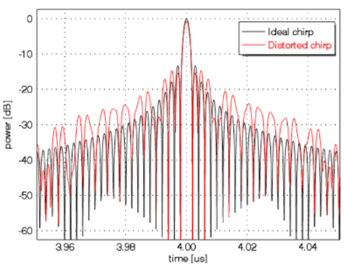


Fig. 3. SPACEBEAM PIC architecture.

The optical beamforming network (OBFN) is an electrically tuneable optical Blass matrix consisting of horizontal and vertical optical waveguides which are inter-connected by reconfigurable nodes implementing tuneable optical phase shifters, see [6]. The optical phase shifters will be controlled by Lead Zirconate Titanate (PZT) piezo-electric actuators deposited on top of the TriPleX waveguides. This solution is baselined because it provides much faster phase shift control than the standard thermal controls, allowing for a 2π phase shift in about 300 ns (instead of hundreds of microseconds), thus permitting the fast-time domain beamforming. In addition the PZT requires lower power compared to the thermal controls which is beneficial for heat dissipation. A key aspect of the SPACEBEAM PIC design is its packaging which needs to provide seamless electrical DC and RF interface for the hybrid assembly while surviving the launch and allowing operation under space conditions. The packaging will be developed and carried out ensuring full compatibility with the state-of-the-art packaging procedures of the European Packaging Pilot Line PIXAPP and will undergo environmental testing for demonstrating the space compliance of the SPACEBEAM solution. More details regarding the PIC architecture and implementation is also provided by [4].

SYSTEM AND PIC PERFORMANCE

Compared to a digital beamforming implementation, the switching between beams cannot be performed instantaneously but will require some minimum time in the order of < 300 ns. The impact on the point target response of the missing data during the switching be-tween beams has been assessed and is shown in Figure 4 and is deemed acceptable.



Switching Time (ns)	ISLR (dB)	Loss (dB)
0	-9.7	0
100	-8.8	-0.2
200	-7.8	-0.4
300	-7.0	-0.7

Fig. 4. Impact on switching of beamforming weights on the IRF.

The SPACEBEAM project is already in an advanced state. The first PICs have been designed, are in production and already partially produced. It is expected that first test results of the beamformer PIC will be presented at the workshop.

APPLICATION TO KA-BAND

The beamforming technology of the SPACEBEAM PIC is frequency-transparent up to 40 GHz allowing its application at the allocated RF band for spaceborne active Earth Observation between 35.5 to 36 GHz. However, SPACEBEAMs system requirements and architecture translated to Ka-band results in the need of a larger number of antenna elevation channels due to the shorter wavelength which translates into more inputs to the PIC. This will in turn require a larger Blass matrix OBFN which will increase the chip size. The increased number of controls for the phase shifters, though, would not significantly change the PIC power consumption, since no current is needed by the actuators. The PICs power consumption instead will be driven by the additional SOAs which are employed before each input of the Blass matrix as well as by the chips thermal control. These considerations pose challenges, especially for the packaging which needs to be properly dimensioned and designed since there is a significant increase both in the PIC size and in the RF, IF, and DC inputs and outputs as well as thermal dissipation.

Considering these aspects, the approach to the optical beamformer architecture adopted in the SPACEBEAM Project can be extended to much higher frequencies. Even though the proposed implementation for the X-band is not optimized for working at much higher frequency, the approach does not present inherent limitations for its application to Ka-band SAR such as SKADI the mission proposal of a Ka-band interferometric radar for cold environments.

ACKNOWLEDGEMENTS

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