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RESEARCH PAPER

Simultaneous beam steering of multiple signals based on optical wavelength-selective switch

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A novel, photonics-based scheme for the independent and simultaneous beam steering of multiple radio frequency signals at a wideband phased-array antenna is presented. As a proof of concept, a wavelength-selective switch (WSS) is employed both as a wavelength router to feed multiple antenna elements and as a tunable phase shifter to independently control the phase of each signal at any antenna element. In the experiment, two signals at 12.5 and 37.5 GHz are simultaneously fed to the four output ports of the WSS with independent and tunable phase shifts, emulating the independent steering of two signals in a four-element phased-array antenna. The results confirm the precision and flexibility of the proposed scheme, which can be realized both with bulk components or resorting to photonic integrated circuits, especially for wide-band applications. The architecture for a possible integrated implementation of the proposed solution is presented, employing a structure based on micro-ring resonator. Starting from these results, the feasibility of an integrated version of the presented architecture is also considered. The proposed photonic integrated circuit realizing the beam-forming network might be based on tunable true-time delay, as well as on phase shift through micro-ring resonators, and could be conveniently implemented with CMOS-compatible silicon technology.

Keywords: Microwave photonics, Technologies and devices, Circuit design and applications

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I. INTRODUCTION

Beamforming is becoming a crucial issue for a number of radio frequency (RF) applications, ranging from wireless access networks to radars. In particular, antennas with non-mechanical beam-steering capabilities are required, in order to finely control their pointing directions without physically moving the antenna. Phased-arrayed antennas (PAAs) are composed by several discrete elements and allow us to obtain the desired beam-forming functionality, by controlling the phase of the RF signal at each antenna element. Active PAAs are attracting a growing interest thanks to their flexibility, since they are composed by a large number of active transmit/receive modules (TRMs), which can locally modify the phase of the transmitted signals. However, in this kind of PAAs, the cost of the large number of TRMs, the system complexity, and the remotization of the antenna still represent non-negligible issues.

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PAA problems can be addressed by resorting to photonics, instead of focusing on traditional electronic solutions. Indeed, photonics techniques allow us to effectively control the phase of RF signals independently from their frequency, by means of phase shifters (PSs) [1] or true-time delay (TTD) [2, 3]. At the same time, photonics guarantees low weight and dimensions, immunity to electromagnetic interference (EMI), and a relative low cost thanks to its high scalability. Moreover, the inherent broad bandwidth of photonic devices can help in realizing more flexible and frequency-agile systems. Schemes based on high-performance PSs have been demonstrated, but the achieved beam-scanning angle was limited [1]. On the other hand, TTD-based architectures can be implemented either exploiting chromatic dispersion [2], or realizing a network for adaptively switching the signals on paths with different delays [3]. The photonic implementations of the TTD approach have demonstrated to be easier than the electronic ones, but they may require very long spools of optical fiber unless an integrated system is employed. A more flexible implementation employing a programmable bandwidth-variable wavelength-selective switch (BV-WSS) [4] has been presented in [5], working on a single wide-bandwidth RF signal.

Recently, we have proposed a scheme for a beam-forming network (BFN) [6], based on a BV-WSS for the simultaneous and independent beam steering of multiple RF signals. The software-programmable WSS have been exploited as a wavelength router to feed multiple antenna elements, and as a tunable PS to independently control the phase of each signal at any antenna element. Moreover, we experimentally validated the scheme by resorting to bulk components. Independent steering of multiple beams has been proposed in [3] and [7], based on chromatic dispersion in optical fibers, and tunable notch filters and couplers, respectively; these approaches, however, are bulky and suffer from a relatively complex design. In this paper, we provide a brief summary of the experimental results of our previous work [6]; additionally, we suggest two possible integrated implementations based either on PS or on TTD, depending on the bandwidth of the considered signals.

II. CONCEPT

Figure 1 reports the general scheme of the architecture proposed in [6]. M independent RF signals $RF_1 \ldots RF_M$, with central frequencies $f_{RF1}, \ldots, f_{RFM}$, are up-converted to the optical domain by modulating N-independent lasers at wavelength $\lambda_1, \ldots, \lambda_N$ in an electro-optical intensity modulator (IM). After the IM, the optical signal is equally split to $K \times N$-outputs BV-WSSs. The employed BV-WSSs are optical devices based on Liquid Crystal on Silicon (LCoS) technology [4], and are capable of routing the signals to one or more among the N ports, controlling the amplitude and phase of the optical signal at each port, with a pixel resolution of 1 GHz (assumed that the employed optical carriers are in the optical C-band, i.e. about 1.5 μm).

The bulk BFN introduced in [6] is an all-optical signal processing architecture for transmitting M independent signals, composed by K, BV-WSS-based sub-blocks. Processing signals in the all-optical domain allows finely controlling their phase (or, alternatively, their propagation delay). Eventually, a set of $K \times N$ photodiodes (PDs) convert the replicas of each optical sideband (SB) in an RF signal, whose carrier frequency is given by the frequency distance between the kth optical carrier and the SB central frequency. Every PD corresponds to one TRM driving a PAA element and, being the optical phase shifts translated into equivalent RF phase shifts, the overall obtained radiation pattern is composed by several, independently steered lobes.

The core of the presented scheme is the BV-WSS, which enables an arbitrary, reconfigurable phase shift on independent multiple RF carrier signals. The phase shifting accuracy strictly depends on the performance of this device. In a BV-WSS, the input light is spatially dispersed by a diffraction grating on an LCoS pixel grid that processes the incoming optical signal and reflects it back to the grating, where the processed light is focused to the selected output port [4]. Each pixel acts on a portion of the spectrum, whose span depends on the pixel dimension. It processes both amplitude and phase of the signal, since it is possible to finely tune the liquid crystals transparency and refractive index via an applied software-controlled electric field.

A critical issue to be addressed any time optical/electrical conversions are considered is the power efficiency. In particular, losses are important in the down-conversion stage, since for signal up-conversion, an electric driver at the RF input of the electro-optical modulator should ensure the desired modulation depth, provided the modulator response is linear over the input signal dynamic range. The down-conversion process, on the other hand, suffers from the limited responsivity of the PD and from its saturation power, which limits the maximum input optical power and, in turn, the overall conversion efficiency. As usually done in microwave photonics application, a proper management of the amplification stages in the optical [8] as well as in the electrical section may help to get around the problem. Furthermore, a typically suggested approach for improving the optical signal-to-noise ratio, and ultimately increase the power efficiency of the link, is to employ optical single-side-band (SSB) modulation. Furthermore, the RF signals are employed to modulate several continuous wave (CW) lasers, each one with its own power. Hence, by exploiting a multi-carrier approach higher conversion efficiency for the RF signals can be obtained at the expenses of larger number of employed optical CW sources.

The proposed architecture finds its natural application in any field, where a steerable antenna beam is required, ranging from radar to mobile communications. Moreover, this system is suitable for antennas remoting, since the BV-WSSs' output is in the form of an optical signal that can propagate for kilometers over an optical fiber with extremely low losses, negligible distortions, and total immunity to EMI.

III. EXPERIMENTAL ACTIVITY: SETUP AND RESULTS

From an experimental point of view, in [6] we have demonstrated the validity of the proposed architecture by the performance analysis of one sub-block of the overall network. More details of the experimental activity for the validation of the BFN sketched in Fig. 1 can be found in [6]. Here, we report a summary of the obtained results, which can be helpful to introduce the following sections of this paper, with considerations around an integrated implementation of the presented scheme.

In Fig. 2, we report the power spectral density (PSD) of the employed optical signals together with the programmed amplitude and phase response of the BV-WSS. Following a typical radio-over-fiber approach, four CW lasers with 11 dBm output power and 200 GHz spacing are modulated by two RF tones at $f_{RF1} = 12.5$ GHz and $f_{RF2} = 37.5$ GHz (black solid line in Fig. 2), where the four optical carriers with double-sideband modulations at f_{RF1} and f_{RF2} are clearly visible. Inside the BV-WSS, the incoming wavelengths are separated and spatially deflected through a diffraction grating; thereafter, the light impinges on a two-dimensional matrix of liquid crystal pixels, which can independently influence amplitude and phase of the impinging light, and route each pixel output to any of the output ports. The pixels matrix response can be controlled via software, imposing a phase and amplitude mask to each output port. This way, a fine-grained filter is obtained, which can shape optical signals all over the whole C-band (1530–1565 nm). The results obtained with the unmodulated sinusoidal RF carriers are expected to apply also for signals with bandwidth of few MHz, as those employed in remote-sensing applications, where a constant phase shift can be applied over the signal bandwidth without incurring in squinting phenomenon [9].

As depicted in Fig. 2, the phase of every carrier is not modified (i.e., optical phase set at 0°). On the other hand, each

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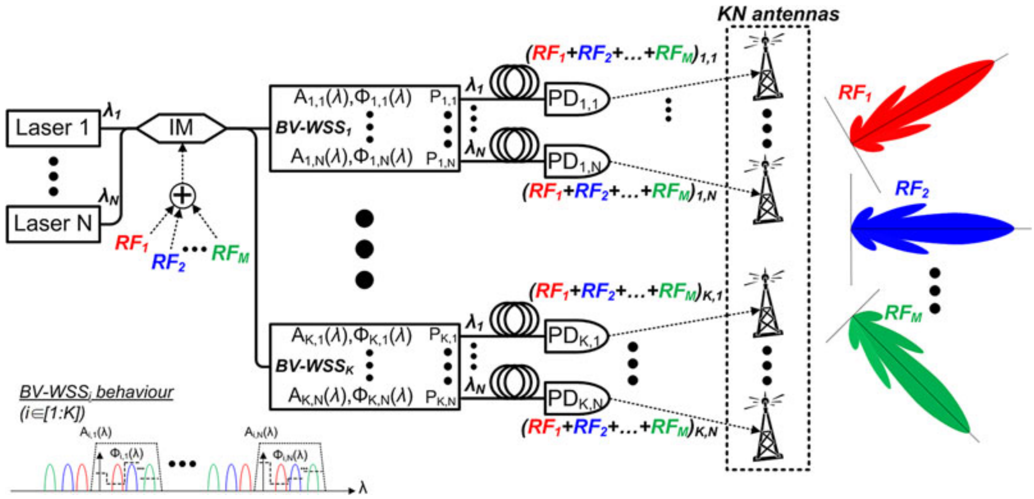

Fig. 1. General scheme for phase-controlled beam steering.

upper sideband (USB) undergoes a different phase shift with respect to the related carrier. The phase of the SBs corresponding to RF_1 ranges from -90° at Port1, to 180° at Port4 increasing by 90°-wide steps. Likewise, the phase of the SBs related to RF_2 decreases by 90° steps from 180° at Port1 to -90° at Port4. Eventually, a 40 GHz-bandwidth PD is used for down-converting the optical signals into the RF domain, thus obtaining four outputs apt to feed four elements of a PAA.

The independent tunable steering of multiple signals has been evaluated by measuring the relative phase shift between the BV-WSS output ports. In the case $f_{RF} =$ 12.5 GHz, a phase shift $\Delta\varphi = \pm 90^\circ$ corresponds to a delay $\Delta\tau = \pm 20$ ps. In the case $f_{RF} = 37.5$ GHz, $\Delta\varphi = \pm 90^\circ$ corresponds to $\Delta\tau = \pm 6.67$ ps. The time delays can be precisely measured by comparing the time markers on the sampling oscilloscope (an Agilent 86100C) [6], or by comparing the oscilloscope traces reported in Fig. 3 The correct behavior of the proposed scheme is demonstrated by the delay imposed between the signals at 12.5 GHz (Fig. 3(a)), and 37.5 GHz (Fig. 3(b)). The measured time shifts exhibited by the signals (rightward for 12.5 GHz, leftward for 37.5 GHz) are ~20 ps for the 12.5 GHz SBs (with an error of ~4%) and ~6.7 ps for the 37.5 GHz SBs (with an error of ~0.45%).

IV. INTEGRATION OF THE PROPOSED ARCHITECTURE

The presented scheme has been realized resorting to bulk devices, typically employed for communication purposes, in order to demonstrate its working principle. The pixels response of the WSS employed in the reported experimental activity is 10 GHz-wide and it turns to be relatively large, actually representing a limitation for the performance of this LCoS technology-based architecture.

The phase transition fronts of the exploited BV-WSS are reported in Fig. 4. A 40 GHz signal has been employed to modulate an optical carrier. A step-like phase transition with variable $\Delta\varphi$ has been imposed between the carrier and its 40 GHz USB. By tuning the carrier wavelength with 0.01 nm steps (1.25 GHz), the USB has been swept across the phase transition, measuring the actual phase shift of the photodetected signal on an oscilloscope, from 0° to the set value of $\Delta\varphi$. The imposed phase steps are actually implemented as ramps. In the case $\Delta\varphi = 90^\circ$ (gray curve in Fig. 4, the transition bandwidth is about 8.2 GHz. If $\Delta\varphi = 180^\circ$ (black curve), the phase transition is steeper, and it spans over about 3.8 GHz. Finally, in the case $\Delta\varphi = 270^\circ$ (light-gray curve), a bandwidth around 6.3 GHz has been measured. If the considered RF signal

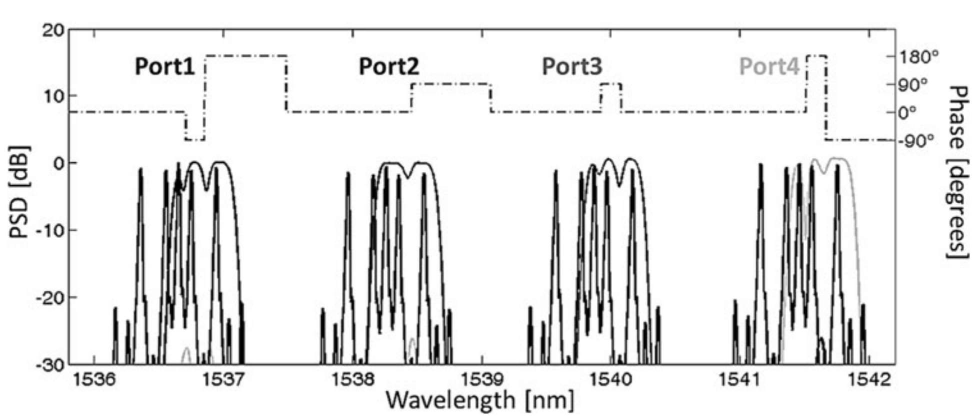

Fig. 2. Optical spectra of the 0.16 nm-spaced input optical carriers modulated at 12.5 and 37.5 GHz (black solid curves), the response of the WSS ports in amplitude (gray dotted lines – refer to the vertical axis on the left) as measured with a wideband, flat noise source. The imposed phase mask is traced by the dash-dotted line (refers to the vertical axis on the right).

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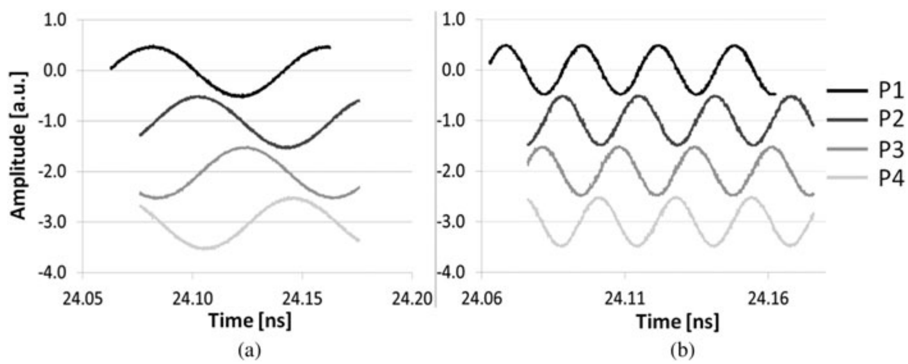

Fig. 3. Oscilloscope traces related to the curves reported in Fig. 4. RF signals at 12.5 GHz (a) and 37.5 GHz (b) from Port1 (P1), Port2 (P2), Port3 (P3), and Port4 (P4), from black to light gray. The legend vertical order follows the order of the offset sinusoidal curves.

has a large bandwidth, it might suffer from a non-uniform phase shift over its spectral components, thus leading to the undesired effect of beam squint. This phenomenon is not an issue if considering applications involving signals with relatively narrow bandwidths, such as radar and remote sensing. In any case, the proposed architecture needs to be further optimized by adopting *ad-hoc* designed devices.

Recently, a small-size and high-resolution BV-WSS has been demonstrated, with 0.8 GHz-bandwidth pixels and 0.2 GHz pixel-to-pixel spacing [10]. Such a device can thus be considered for the improvement of the performance of the proposed architecture, though it represents a miniaturized but not integrated system. In order to obtain an extremely compact scheme, and endow it with complete mechanical robustness, the development of a cost-effective and small-sized BFN based on the proposed architecture inevitably implies optical integration.

The proposed BFN is divided in sub-blocks. In its bulk-components version [6], the phase stability is an issue between the signals summing up from different sub-blocks, since within the same BV-WSS the optical waves propagate together, undergoing the same phase changes. Indeed, no unwanted phase mismatch has been detected and no stability issue arose in the experiment. As regards the amplitude stability issue, a proper equalization is possible thanks to the BV-WSS itself, allowing us to independently control the attenuation at each output port. On the other hand, the inter-sub-blocks phase stability problem is not completely solved by resorting to integrated photonic circuits, since it is not possible to control the circuits dimension with any desired accuracy; however, a feedback-based system can be implemented for an automatic control of the phase shift/time delay imposed by each micro-ring resonator (MRR) [11]. Similarly, the amplitude of the signals propagating through the integrated circuit can be suitably controlled by means of optical attenuator in order to accurately balance the different power losses within each arm.

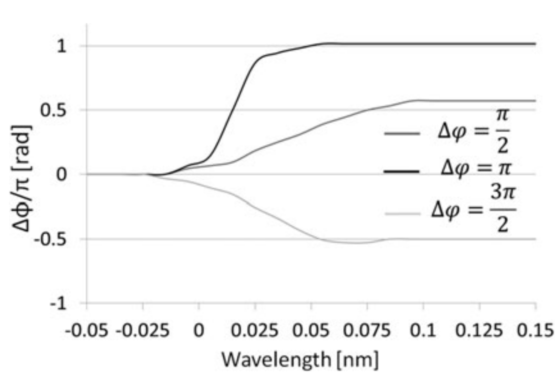

Fig. 4. Measurement of the actual front of the step-like imposed phase shift for three values of $\Delta\varphi$: $\pi/2$ (gray line), π (black line), $3\pi/2$ (light-gray line).

A) Operation principle of the integrated scheme

The chosen approach for realizing an integrated version of the proposed architecture is based on MRRs in an all-pass filter (APF) configuration [12]. A MRR-based APF consists of a resonant cavity implemented with a circular or race-track waveguide, which is connected to input/output ports through a straight bus waveguide. Such a MRR-based APF produces a frequency selective phase-response, which results in a bell-shaped group delay (GD) response (i.e., the derivative of the phase with respect to angular frequency) centered at a resonant wavelength of the cavity. MRR-APF can be conveniently fabricated for instance with low-loss, CMOS-compatible, silicon over insulator (SOI) or silicon nitrade (SiN_x) technologies. The optical properties of the MRR, i.e. its phase/GD response, can be tuned by varying the coupling strength between the ring and the bus straight waveguide, which can be achieved by means of variable couplers [13]. Further, the resonant wavelength of the cavity can be tuned by introducing a differential optical path change, i.e. a phase shift for the field circulating in the cavity, by acting on the refractive index of the waveguide. A viable solution for the realization of a phase shift in SOI/SiN_x-based MRR is to exploit the strong thermo-optic effect in silicon, through metallic heaters placed above the ring cavity.

B) The multicarrier integrated optical BFN

The structure of a multicarrier, multibeam, integrated BFN is sketched in Fig. 5, representing an integrated version of the one reported in Section II and depicted in Fig. 1. As shown in the figure, N different optical carriers, each with M SBs, generated through single-sideband (SSB) optical modulation, are considered. The signals are fed into a wavelength demultiplexer (DEMUX) stage that can be suitably integrated within the circuit resorting to the same technology as for MRRs, and which is responsible for separating the different carriers and respective SBs at its N output ports. After the

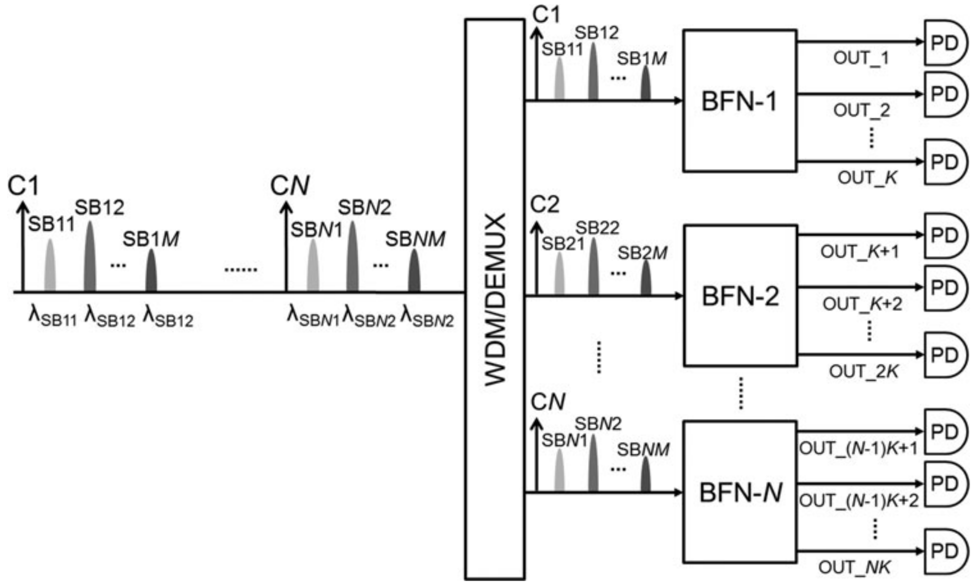

Fig. 5. Integrated BFN general scheme. SB, Side Band; DEMUX, Demultiplexer; BFN, Beam-forming Network. PD, Photodiode.

DEMUX block, each optical carrier, together with its SBs, is routed to a BFN. There, the carrier and SBs comb is equally split over K-separated paths, and each SB propagates in one or more different MRRs, undergoing to a different phase shift, similarly to what described in the previous sections, where the BV-WSS-based BFN is illustrated. At the outputs of the BFNs, a PD drives the radiating elements of one out of K different PAAs, each composed by an array of N elements. The BFN blocks can be implemented employing MRRs, in two different ways: either resorting to PS or to TTD.

An integrated implementation of the proposed architecture, exploiting PS for beam steering, can be obtained referring to the scheme sketched in Fig. 6. One optical carrier λ_j out of the N wavelengths considered in Fig. 5 enters the kth BFN. For the sake of simplicity, only three modulated sidebands (SB_{ji} in the figure) are depicted, and SSB modulation is assumed. This BFN is based on MRRs to implement add/drop (A/D) blocks and the phase shift blocks. As previously mentioned, by slightly adjusting the resonant frequencies of the MRRs, by means for instance of thermal heaters, a different phase shift $\Delta\varphi_{jik}$ can be introduced over each SB (where $1 \leq i \leq M$, $1 \leq j \leq N$, $1 \leq k \leq 4$). As depicted in the figure, at the first A/D stage, SB_{j3} is dropped and propagates toward the MRR imposing the desired phase shift $\Delta\varphi_{j3k}$. Similarly, the remaining SBs are dropped one by one and each of them undergoes to a controlled phase shift $\Delta\varphi_{jik}$ thanks to the MRRs. All the optical signals are eventually recombined, making them beat in a PD, converting the SBs back to the RF domain to feed an element of the PAA. Thus, the different-phase radiated RF signals sum up, producing a beam with the desired orientation. The phase relations between the signals and the carrier can be accurately controlled thanks to a feedback network driven by the PD output, as shown in Fig. 6. RF signals phase can be measured much more easily, thus mitigating the problem of undesired phase mismatch.

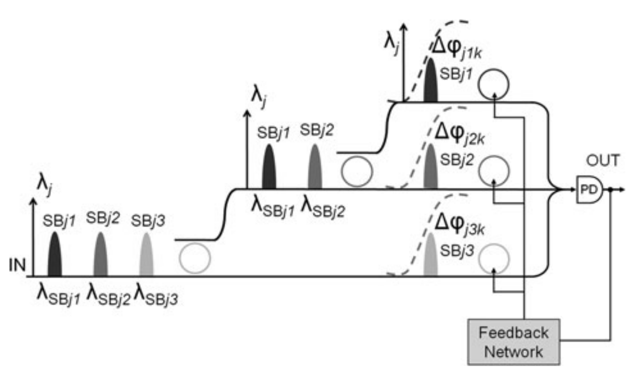

Fig. 6. Integrated version of the proposed BFN architecture, based on MRRs. The phase response profile of the MRRs, ranging in the 0–2π interval, is sketched. $\Delta\varphi_{jik}$ is the phase shift on the ith SB of the jth optical carrier on the kth demux output. SB, Side Band; PD, Photodiode.

With respect to the bulk architecture presented in the previous sections, the MRR-based implementation offers the possibility of providing a TTD instead of PS, for the signals traversing the ring structure, thus making it suitable also for broad-band signals and/or large array size, should the beam squint [14] represent an issue. The operation principle for the TTD-based integrated version of the BFN is schematized in Fig. 7, which extends to a multi-channel scenario the binary-tree architecture that has been proposed in [15]. Here again, for the sake of clarity and without any loss of generality, we can still consider one optical carrier λ_j, which is SSB modulated by two RF signals to generate two SBs (SB_{j1} and SB_{j2} in the figure). Similarly to the previous scheme, the optical signal is split over four different paths, in which MRRs are used to provide different values of group delay. The amount of GD can be increased without sacrificing the useful bandwidth by cascading two or more rings with slightly detuned resonant frequencies [16]. A dedicated ring cascade for each SB is present on each path. As discussed, the couplers and the time delays in the MRRs can be properly tuned thermally, in order to provide the desired GD response at the wavelength corresponding to either SB_{j1} or SB_{j2}, leaving unaffected the other signal. In particular, in the topmost path (from IN to OUT1), the first ring (deep gray) delays only SB_{j1} by a certain GD τ_1, whereas the second ring (light gray) delays only SB_{j2} by a different GD τ_2. Similarly, on the

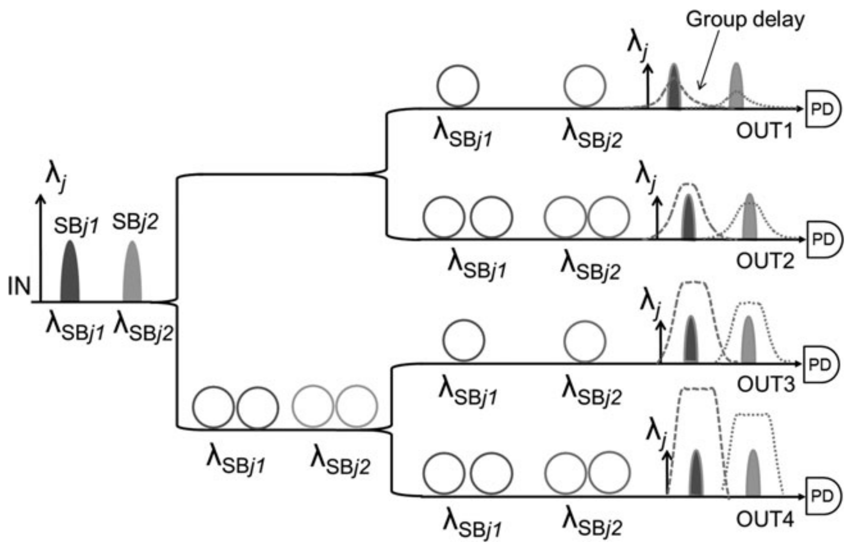

Fig. 7. Working principle of the integrated BFN based micro-ring resonators. The dashed and dotted curves represent the cascaded MRRs overall response, in terms of GD, for two different wavelengths. SB, Side Band; PD, Photodiode.

following lower path, a cascade of two couples of properly shifted MRRs is used to produce a GD of $2\tau_1$ and $2\tau_2$ for SB_{j1} and SB_{j2}, respectively. Following this principle, for K-outputs BFN, the signal SB_{ji} coming out from OUT-K, is delayed by $K\tau_i$; thus, an increasing GD with constant independently tunable steps going from OUT1 to OUT4 can be achieved for both SBs [15]. After being delayed in the optical domain, the signals eventually beat in the PDs, generating an RF copy of SB_{j1} and SB_{j2}, by means of an optical down-conversion process, with a central frequency equal to the difference between the carrier and the SBs optical frequency. The output of each PD can thus be used to feed a PAA element and, by the superposition of the RF signals radiated from each element, the steering of every transmitted signal is effectively achieved. By changing the delay τ_i of each path and by acting on the MRR phase and coupling strength, the RF signal can thus be steered at any direction, with a typical sub-ps resolution for the induced delays.

V. CONCLUSIONS

In this paper, we have proposed a novel scheme exploiting signal processing at a photonic level for realizing the independent and simultaneous beam steering of multiple RF signals. Starting from the scheme proposed in [6], which is based on the use of BV-WSSs, here we propose integrated implementations of that architecture. BV-WSS allows controlling via software the spectral shaping of the optical amplitude and phase at each output port; the integrated architecture can perform either PS or TTD, depending on the bandwidth of the signals the BFN is designed for.

The capability of the proposed system for simultaneously obtaining an independent, tunable steering of different signals has been exhaustively demonstrated, also assessing the degree of precision of the phase control. However, the exploited BV-WSS is a device purposely designed for optical wavelength division multiplexing communication systems, and we believe that a specific design for beam-forming applications could achieve better performance. The scheme therefore appears as a promising solution for feeding the numerous TRMs in a phased-array antenna, digitally controlling the direction of several RF signals simultaneously and independently.

One of the integrated proposed versions of the multi-beam BFN exploits MRRs to implement A/D blocks as well as tunable PS elements, orienting the beam-forming strategy on PS. Alternatively another integrated design has been considered, exploiting TTD and integrated optical splitters, ideal for dealing with broadband signals.

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