This work presents an integrated microwave photonic splitter with reconfigurable amplitude, phase, and delay offsets. The core components for this function are a dual-parallel Mach-Zehnder modulator, a deinterleaver, and tunable delay lines, all implemented using photonic integrated circuits. Using a demonstrator with an optical free spectral range of 25 GHz, we show experimentally the RF splitting function over two continuous bands, i.e. 0.9–11.6 GHz and 13.4–20 GHz. This result promises a deployable solution for creating wideband, reconfigurable RF splitters in integrated forms.

**OCIS codes:** (060.5625) Radio frequency photonics; (130.3120) Integrated optics devices; (130.4815) Optical switching devices; http://dx.doi.org/10.1364/OL.99.099999

Integrated microwave photonics (IMWP) is providing a new and promising path for RF engineering by utilizing a broad range of photonic functions in integrated forms [1, 2]. Besides the unprecedented features of large instantaneous bandwidth, easy implementation of tuning, and reduced electromagnetic interference, IMWP enables RF functions with small size, weight, as well as power consumption, and allows for software-defined signal processing functions in one integrated device [3] (analogues to programmable electrical signal processors). This shows strong potential of commercial adoption in future RF communication and sensor systems and networks [4, 5].

Here, we present a wideband 1×2 RF splitter with reconfigurable amplitude, phase, and delay offsets between its two outputs, based on photonic integrated circuits (PICs). While difficult to achieve using conventional electronic integrated circuit technologies due to limited tuning capabilities [6–9], reconfigurable RF splitters can be realized in compact forms, resorting to IMWP technologies. These are a useful function with great application potential. For instance, the splitter can be applied for simultaneous generation of “I” and “Q” signals with a wide frequency coverage for coherent RF communication and radar systems [10]. Another example is to use the splitter as a reconfigurable feeding network for dual-linear antennas, which provides each antenna component an independent complex coefficient (arbitrary phase and amplitude) to enable electrically-controlled polarization-switching function [11] (e.g. switching between linear and circular polarizations by controlling the inter-component phase difference).

A number of microwave photonic phase shifters and delay lines have been introduced using various devices, such as spatial light modulators [12], fiber and waveguide gratings [13–15], semiconductor optical amplifiers [16, 17], waveguide ring resonators [18, 19], polarization modulators [20, 21], and fibers with stimulated Brillouin scattering [22, 23]. However, when applied into a 1×2 arbitrary-offset RF splitter, these approaches will in general lead to doubled system complexity for using two times phase shifters and/or delay lines. Besides, most of them will require independent controls of RF amplitude, phase, and delay for each output, incurring additional engineering effort. Recently, some of us presented the concept of a reconfigurable microwave photonic splitter allowing for arbitrary amplitude and phase offsets [24]. It utilizes a simple tuning mechanism in a dual-parallel Mach-Zehnder modulator (DPMZM) [25], and allows for broadband operation. However, the first demonstration of that concept comprises a bulky and expensive arrangement of discrete photonic devices, such as a spatial light modulator-based optical signal processor and two lasers.

In contrast, the IMWP approach we present in this work reduces the bulky system into a PIC-based solution that requires only one laser and provides delay offset as an additional dimension of reconfigurability. It improves the optical processing resolution to the sub-GHz regime, and has clear potential for single-chip integration as well as for functional extendibility. This owes to the fact that all the constituent components are common photonic integrated circuit building blocks and can be designed with reconfigurability [1, 2].

Figure 1 depicts the system configuration of the RF splitter. A CW laser provides an optical carrier frequency, $\omega_{\text{opt}}$. It is modulated by an RF input such that the output spectrum comprises of two RF sidebands and an optical carrier that has an independently adjustable phase. The process for achieving such modulation spectrum is shown in the insets (i) to (ii) of Fig. 1. For simplicity, we restrict here to the case of small
signal modulation, so that only the first-order sidebands need to be taken into consideration [26]. Here, the optical carrier is first split into two separate paths. In one path, two RF sidebands are created by means of double-sideband suppressed-carrier (DSB-SC) modulation. In the other path, a phase control of 0 is applied to the optical carrier. Then, the recombination of the two paths results in the desired spectrum. Subsequently, the modulated optical signal is sent to a dedicated deinterleaver, where the whole spectrum is cut into two parts and fed respectively to the two deinterleaver outputs. The filter response of the deinterleaver is designed such that each output let through one of the sidebands and a portion of the optical carrier as shown in the insets (iii) and (iv) of Fig. 1. In effect, each output contains a single-sideband-modulated optical carrier [18]. By means of direct detection, the beat product of the optical carrier and lower sideband results in an RF phase shift, respectively. For providing circuit reconfigurability [1], the phase of the optical carrier and RF signals, and assume that the deinterleaver introduces no amplitude and phase distortions over the sidebands. Then the two photodetector outputs, \( I_{\text{out1}} \) and \( I_{\text{out2}} \), can be derived from (4) and (5), respectively, as

\[
I_{\text{out1}} = \sqrt{\rho_1} \eta m(t) \cos(2\pi f_{\text{RF}} (t + \Delta t_1) + \Delta \theta)
\]

\[
I_{\text{out2}} = \sqrt{\rho_2} \eta m(t) \cos(2\pi f_{\text{RF}} (t + \Delta t_2) - \Delta \theta)
\]

where \( \eta \) represents a common RF amplitude factor determined by the input optical power and photodetector responsivity [26]. Evidently, such a system works as a 1 \times 2 RF splitter with the amplitude, phase and delay offsets governed by the parameters, \( \rho_n, \Delta \theta_n, \) and \( \Delta t_n \). Moreover, in the case that the deinterleaver provides periodic passbands along the frequency, the system explained above is able to operate at multiple RF bands within the bandwidths of the modulator and photodiode.

Figure 2 depicts our implementation of the modulator, deinterleaver and delay lines as photonic integrated circuits. For the DSB-SC modulator and carrier manipulation, we use a dual-parallel Mach-Zehnder modulator (DPMZM) comprising two Mach-Zehnder modulators (MZM1 and MZM2). As illustrated, in the upper arm, MZM1 is driven by the RF input signal and biased (via Bias 1) for DSB-SC modulation; in the lower arm, MZM2 and an independent optical phase shifter are biased (via Bias 2 and Bias 3) respectively for controlling the amplitude and phase of the optical carrier.

The deinterleaver is realized via a Mach-Zehnder interferometer assisted with two ring resonators (2RAMZI), with their ring loops being twice as long as the differential arm length of the MZI [11]. In terms of signal processing these circuits can be modeled as digital filters [28] whose \( z \)-transform transfers are given by

\[
H_{2\text{RAMZI}} = \begin{bmatrix} H_{11}(z) & H_{12}(z) \\ H_{21}(z) & H_{22}(z) \end{bmatrix}
\]

\[
= \delta \begin{bmatrix} \sqrt{-1} & -j \sqrt{-1} \\ -j \sqrt{-1} & \sqrt{-1} \end{bmatrix} A_1(z) 0 \begin{bmatrix} \sqrt{-1} & -j \sqrt{-1} \\ -j \sqrt{-1} & \sqrt{-1} \end{bmatrix} A_2(z)
\]

\[
= A_1(z) \begin{bmatrix} \sqrt{-1} - \kappa_R & -\gamma \gamma z^{-2} - e^{-j \phi} \\ -j \sqrt{-1} & \sqrt{-1} \end{bmatrix} A_2(z)
\]

where \( \kappa_n \) and \( \phi \) express the power coupling coefficient and phase shift respectively. For providing circuit reconfigurability [1], \( \kappa_n \) and \( \phi \) are controlled using phase tuning elements as illustrated in Fig. 2.

To provide an experimental verification, we realized a laboratory demonstrator of the proposed splitter. The setup uses a narrow bandwidth CW laser at 15 μm wavelength (AlnairLabs TLG-300M), a
The deinterleaver and delay lines comprising four cascaded ring resonators are fabricated on a single chip, in a commercial Si3N4 waveguide platform [TriPlex] [29, 30], with a common FSR design of 25 GHz. Chromium heaters on top of the waveguide enable thermal-optical phase tuning [1]. The chip coupling is optimized for TE polarization. The total fiber-to-fiber insertion loss amounts to 9 dB, dominated by two times fiber-coupling losses of about 4 dB/facet. However, this value is expected to decrease significantly, to about 1 dB/facet [31] when a particular design of waveguide facet or interposer is used to optimize the coupling efficiency. Figure 3 depicts the waveguide mask layouts and measured frequency responses of the deinterleaver and delay line. The corresponding circuit parameters are listed in Table 1.

Table 1. Circuit parameters for the frequency responses in Fig. 3.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>2RAMZI</th>
<th>SCISSOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>$\kappa_1$</td>
<td>$\alpha_1$</td>
</tr>
<tr>
<td>$\kappa_1$</td>
<td>0.5</td>
<td>0.70</td>
</tr>
<tr>
<td>$\kappa_2$</td>
<td>0.5</td>
<td>$\phi_1$</td>
</tr>
<tr>
<td>$\phi_1$</td>
<td>0.87</td>
<td>0.76</td>
</tr>
<tr>
<td>$\phi_2$</td>
<td>$\phi_1$</td>
<td>0.76</td>
</tr>
<tr>
<td>$\phi_3$</td>
<td>$\alpha_2$</td>
<td>Arbitrary</td>
</tr>
<tr>
<td>$\phi_4$</td>
<td>$\alpha_3$</td>
<td>0.70</td>
</tr>
<tr>
<td>$\phi_5$</td>
<td>$\alpha_4$</td>
<td>0.48</td>
</tr>
</tbody>
</table>

As shown in Fig. 3(c), the deinterleaver (2RAMZI) provides periodic passbands, allowing the system to operate at multiple RF bands. However, due to the bandwidth limitation of the modulator and photodiodes in our system, only two of these RF bands are selected in this work. This selection is motivated as follows. As explained in [11], the parameter setting in Table 1 configures the 2RAMZI into a 5th-order Chebyshev-Type-II filter. Such a filter is characterized by a flat passband with a -0.5 dB-bandwidth equal to 47% of the FSR, an equal-ripple stopband with suppression of 25 dB, and a sharp transition bandwidth (from -0.5 dB to -25 dB) equal to 7% of the filter -3 dB bandwidth that accounts for half of the FSR. Based on our circuit FSR of 25 GHz, these features translate to a transition bandwidth of 0.9 GHz and an effective RF bandwidth of 10.7 GHz for each deinterleaver passband, considering the optical carrier is positioned within a transition band and both RF sidebands are covered in the -0.5 dB-passbands. Fig. 3(d) depicts the measured two group delay responses of the SCISSOR with delay values of 0 ns and 0.2 ns for a bandwidth of 13 GHz. These are configured to be wider than the deinterleaver passband and therefore guarantee that the entire RF sideband is covered in the delay band. When required, a larger delay tuning range can be provided by increasing the number of ring resonators [1, 27, 28]. Due to the loss in the waveguide, the total loss of the delay line increases in a near-linear manner with the delay value [30]. In our experiment, a delay of 0.2 ns induces a loss about 0.5 dB.

With the DPMZM, deinterleaver, and delay lines properly configured, we performed a measurement of the RF transmission of the demonstrator system (scattering parameter $S_{21}$), using a vector network analyzer (Anritsu 37247D). As shown in Fig. 3c, the optical carrier was initially positioned in the middle between the transition bands of the two deinterleaver outputs, i.e., at the -3 dB position with respect to both $H_{11}$ and $H_{21}$, corresponding to equal optical carrier splitting coefficients, $\rho_1 = \rho_2$ (Fig. 1). Two RF sweeping bands were used, i.e. 0.9 to 11.6 GHz and 13.4 to 20 GHz (limited by the maximum frequency of the measurement equipment). The measurement system was calibrated to remove the effect of the RF cables. Figure 4(a) depicts the RF phase responses of the system, where the initial phase offset between the two outputs is removed for clarity. For this measurement, the delay lines were bypassed by using the 0-ns setting, and RF phase offset with a continuous and full tuning range of $2\pi$ was demonstrated by continuously changing the optical carrier phase via Bias3 of the modulator. Figure 4(b) depicts the RF power responses of the system. Here, we demonstrate the function of a tunable amplitude offset, which was performed by varying $\rho_1$ and $\rho_2$ through frequency-shifting the deinterleaver response (equivalent to changing the position of the optical carrier in the transition band of the deinterleaver). When the deinterleaver response (Fig. 3c) shifts to a lower frequency, $\rho_1$ for Out 1 decreases as the optical carrier becomes closer to the stopband of $H_{11}$, whereas $\rho_2$ for Out 2 increases as the optical carrier becomes closer to the passband of $H_{11}$. This will be vice versa when the deinterleaver response shifts to a higher frequency. The frequency shift was implemented using the heaters that control $\phi_{he}$ of the 2RAMZI and $\phi_{he}$ of the SCISSOR to shift the delay line. As an example, an output was provided with an additional delay of 0.2 ns as shown in Fig. 3d. Then, an RC phase slope difference is obtained as expected between the two outputs. The delay change was performed using the heaters for $\kappa_1$ and $\phi_1$. The results in Fig. 4 clearly prove the continuous reconfigurability of the amplitude, phase, and delay offsets of the RF splitter function. As all the tuning elements in the system (modulator biases and circuit heaters) are driven by DC voltages, a simple multi-channel DC supply can be used for system configuration. For the voltage control, a microcontroller and a look-up table can be employed as a possible approach.
therefore achieving a system gain and dynamic range that outperform PROMIS2DAY (I
from a number of previous works showing the integration of similar PIC
building blocks by means of micro-assembly of chips of different
Funding.
with reconfigurable amplitude, phase and delay offsets. The system is
expected to be realized as a stand-alone device and have great
application potential in the wideband RF communication systems.
Fig. 4. RF transmission measurements (scattering parameter S21) of
the system for RF bands 0.9 to 11.6 GHz and 13.4 to 20 GHz: (a)
continuous tuning of phase responses (Δϕ: modulator DC halfwave
voltage), (b) continuous tuning of power responses, and (c)
continuous tuning of phase responses showing the delay effect.
for the parameter tuning process. Our demonstrator chip has a power
dissipation about 150 mW/Chip (using the heater design as in [1,18,
19, 30]). However, for such passive-function PICs, alternative
implementations of phase tuning have been demonstrated recently
with multiple-orders-of-magnitude reductions of power dissipation
[32, 33], which are highly promising for practical applications.
The proposed system is in nature a microwave photonic link,
therefore achieving a system gain and dynamic range that outperform
the current all-electronics RF processing systems remains a challenge
[34]. These issues require further improvement of the optoelectronic
components [26]. In terms of device realization, the proposed system
has the potential to be fully integrated on the chip level. This can be seen
from a number of previous works showing the integration of similar PIC
building blocks by means of micro-assembly of chips of different
technologies [31, 35, 36] or monolithic integration on one waveguide
platform such as InP [37].
In conclusion, we have demonstrated a wideband 1 × 2 RF splitter
with reconfigurable amplitude, phase and delay offsets. The system is
expected to be realized as a stand-alone device and have great
application potential in the wideband RF communication systems.
Funding. This work is funded by Australian Research Council Laureate
fellowship (FL13010041) and Dutch Agentschap NL IOP project
PROMIS2DAY (IPD12009).

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