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# Optical RF Phase Shifter Design Employing Optical Phase Manipulation and Coherent Detection – Part I: Concept Proposal

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***Abstract-* An optical radio-frequency (RF) phase shifter concept employing optical phase manipulation of a double-sideband (DSB) modulated optical signal and coherent detection is proposed in this paper. The technique performs broadband electrical phase shifting directly in the optical domain. Its principles of operation as a standalone sub-system enable electrical phase shifting to be performed on the DSB modulated optical signal unrestrictedly at any location in an RF photonic network. It has low RF phase error and no output amplitude-phase interdependency. The numerical analysis and demonstration of this optical RF phase shifter, utilizing an industry-standard photonic simulator, will be presented in a separate report.**

***Index Terms*- RF photonics, microwave photonics, optical RF phase shifter, photonic microwave phase shifter, photonic signal processing, analogue signal processing.**

## I. INTRODUCTION

Photonics is attractive for broadband transmission and processing of radio-frequency (RF) signals taking advantage of the low in-fiber attenuation and wide bandwidth [1]-[2]. RF photonics is a technology platform that enables simultaneous distribution and analogue processing of the RF signals of interest directly in the optical domain [3], as illustrated in Fig. 1.

The requirements of high-capacity optical communications systems are the key drivers for RF photonics, but it has also found niche exploitation in other domains including defence applications [4]. The frequency of the RF signals of interest can range from 1 to 100 GHz, but is often restricted by the electrical bandwidths of commercial-off-the-shelf (COTS) Mach-Zehnder electro-optic modulators (EOMs) and photodetectors (PDs).

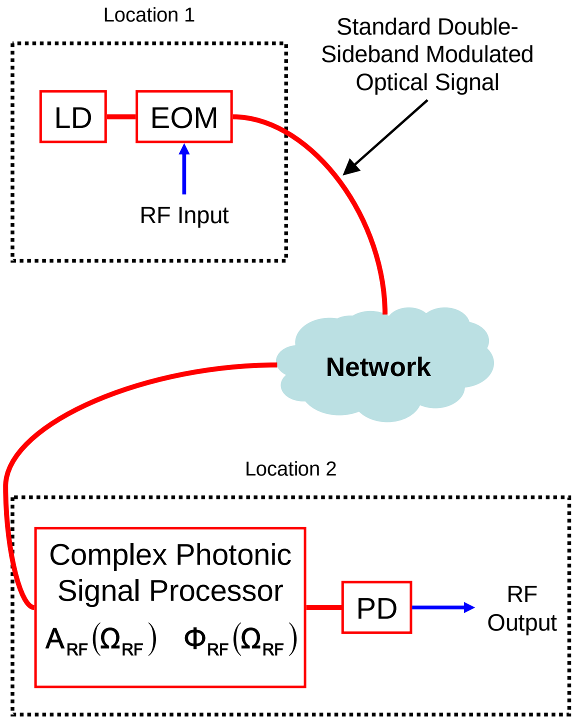


Fig. 1. Optical distribution and complex processing of RF signals. LD, laser diode; EOM, electro-optic modulator; PD, photodetector; $\Omega_{RF}$, RF signal angular frequency; $A_{RF}$, RF amplitude transfer function and $\Phi_{RF}$, RF phase transfer function.

The basic building block depicted in Fig. 1 is the RF photonic link consisting of a laser diode (LD), EOM, optical fiber and PD. The RF signal is first amplitude modulated on an optical carrier through the EOM. This produces a double sideband (DSB) modulated optical signal, the most common implementation in analogue RF photonics, which then propagates through the optical fiber. The RF signal is recovered with a PD. It can be appreciated that engineering benefits can be gained if essential complex signal processing of the RF signal can be performed directly in the optical domain prior to the output PD [3]. This requires both RF amplitude and phase manipulation or control, which is represented by the arbitrary RF amplitude and phase transfer functions, $A_{RF}(\Omega_{RF})$ and $\Phi_{RF}(\Omega_{RF})$, as illustrated in Fig. 1 where $\Omega_{RF}$ is the RF signal angular frequency.

In the optical domain, the RF amplitude processing can be implemented with relative ease. Minasian [5] provides highlights of recent progress in the area of advanced analogue photonic signal processing. However, arbitrary optical RF phase control is more difficult to implement. A particular challenge is the system engineering requirement associated with the separation between the RF front-end (input) and back-end (output), as illustrated in Fig. 1. An ideal photonic signal processor simply manipulates the DSB modulated optical signal present at its input. In such case, design parameters such as the number of laser wavelengths and their tuneability cannot be used as control parameters. Often, this RF input-output separation is a consideration missing from the development of advanced analogue photonic signal processing techniques. A black-box approach, where there is no RF input-output separation, has some value. However, there are unaddressed demands for novel photonic signal processing techniques that can be utilized as illustrated in Fig. 1. In addition, the author would like to suggest an applicability test for any optical RF phase shifter design based on whether it could potentially be utilized as an integral part of the complex taps of high-order delay-line filter designs as described in [5].

Optical RF phase shifting techniques that have been reported can be categorized into the following four types; true-time delay [6]-[7], vector-sum method [8]-[17], nonlinear optic [18]-[24] and coherent detection [25]-[28]. The use of true-time delay for optical RF phase shifting [6]-[7] is narrowband by nature and hence its usefulness is limited. By far the most popular reported method for optical RF phase shifting is the vector-sum method [8]-[17], which uses the well-known *Harmonic Addition Theorem*:

$$\begin{aligned} & a\cos(\theta)+b\sin(\theta) \\ & =\operatorname{sgn}(a)\sqrt{a^2+b^2}\cos\left[\theta+\tan^{-1}\left(-\frac{a}{b}\right)\right] \end{aligned} \tag{1}$$

The vector-sum method relies on the generation of in-phase (cosine) and quadrature (sine) RF signal derivatives by using a conventional electronic 90-degree hybrid coupler prior to modulation on to separate optical carriers and eventual summation at the output PD [8]-[17]. In this case, there is no bandwidth advantage for performing analogue signal processing in the optical domain since the 90-degree hybrid coupler is often the bandwidth-limiting component. It is also clear from (1) that there is a strong relationship between the output amplitude, $\sqrt{a^2+b^2}$, and output phase change, $\tan^{-1}(-a/b)$. From a practical and systemic point of view, this output amplitude-phase interdependency imposes the need for complicated automatic gain equalization schemes to accompany vector-sum optical RF phase shifters.

A recent development in optical RF phase shifting is the application of nonlinear optics ranging from stimulated Brillouin scattering (SBS) [18], nonlinear optical loop mirror (NOLM) [19], ring resonators [20]-[21] and slow- and fast-light effects in semiconductor optical amplifiers (SOAs) [22]-[24]. The application of nonlinear optics for optical RF phase shifting is still in its infancy. Apart from the complexity of the topology, solutions based on nonlinear effects, such as stimulated Brillouin scattering, often require long lengths of optical fiber which would consequently give rise to latency issues. The slow- and fast-light effects in SOAs are highly promising since they can solve the problem of RF input-output separation. However, the SOA-based solution does suffer from significant amplitude-phase interdependency [22]-[24], similar to the vector-sum method discussed earlier.

Last but not least is the combination of optical phase manipulation and coherent detection [25]-[28]. In particular, Stulemeijer *et al.* [26] described the feasibility of a compact photonic integrated circuit for controlling phase and amplitude of a phased-array antenna. It highlighted the ability to perform RF phase shifting through the manipulation of optical phase and coherent detection with electronic control signals, which has matching characteristics to the ideal optical RF phase shifter illustrated in Fig. 1 to warrant further exploration. Furthermore, the potential of the technique to be implemented in integrated photonic circuitry is highly attractive high-order delay-line filters as described in [5].

In this paper, an optical RF phase shifter concept employing optical phase manipulation of a DSB modulated optical signal and coherent detection is proposed. The main objective is to design an optical RF phase shifter that functions in a similar manner to a conventional COTS RF phase shifter. The proposed optical RF phase shifter design is shown qualitatively to have very low RF phase error and no output amplitude-phase interdependency.

The report is structured in the following manner. Section 2 provides the theory, while Section 3 presents the proposed design of the optical RF phase shifter concept. Section 4 presents additional discussion and a brief introduction of the follow-up report summarizing the numerical demonstration.

## II. THEORY

The following equation for the optical field of a generic DSB modulated signal is assumed:

$$\begin{aligned} E(t) = {} & Be^{j(\omega_o - \Omega_{RF})t} \\ & + Ae^{j\omega_o t} \\ & + Be^{j(\omega_o + \Omega_{RF})t} \end{aligned} \qquad (2)$$

where $\omega_o$ is the optical angular frequency, $\Omega_{RF}$ is the RF angular frequency, $A$ is the field amplitude of the optical carrier and $B$ is the field amplitude of both lower and upper sidebands. The optical field strengths $A$ and $B$ relate to the Bessel functions of the first kind $J_0(\pi V_{in}/V_\pi)$ and $J_1(\pi V_{in}/V_\pi)$, respectively, where $V_{in}$ is the RF drive voltage and $V_\pi$ is the half-wave voltage of the EOM. In this case, the optical carrier and sidebands are in-phase with each other. Detection with a square-law PD gives a fundamental alternating current (AC) output:

$$I_{\Omega_{RF}}(t) \propto 4AB\cos(\Omega_{RF}t) \qquad (3)$$

Note that (2) is an ideal representation and it only acts as a tool to keep the analysis simple. What matters is the principle of optical RF phase shifting presented in this analysis. The DSB modulation format is used because it is the most common in analogue RF photonic signal processing. Using only one sideband of the DSB modulated signal would simply incur a RF power penalty of 3 dB.

Now the following optical phase manipulation on the individual carrier and sidebands is considered:

$$\begin{aligned} E(t, \Phi_{RF}) = {} & Be^{j[(\omega_o - \Omega_{RF})t - \Phi_{RF}]} \\ & + Ae^{j\omega_o t} \\ & + Be^{j[(\omega_o + \Omega_{RF})t + \Phi_{RF}]} \end{aligned} \qquad (4)$$

or alternatively,

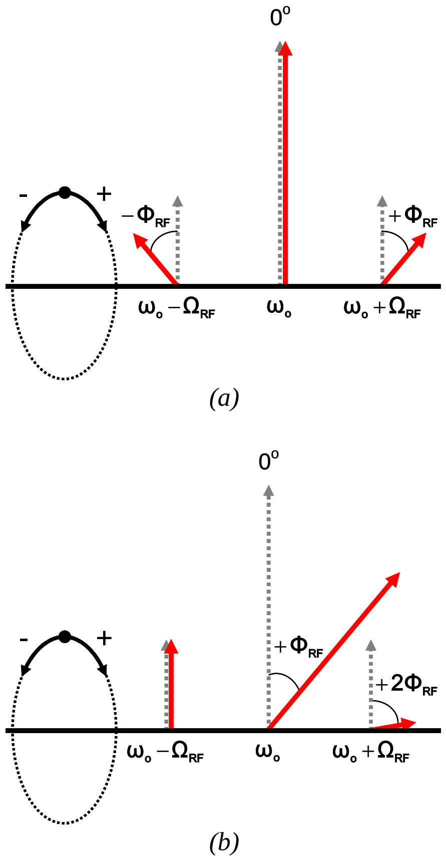
$$\begin{aligned} E(t,\Phi_{RF}) = {} & Be^{j(\omega_o-\Omega_{RF})t} \\ & + Ae^{j[\omega_o t+\Phi_{RF}]} \\ & + Be^{j[(\omega_o+\Omega_{RF})t+2\Phi_{RF}]} \end{aligned} \tag{5}$$

where $\Phi_{RF}$ is the magnitude of the optical phase required to achieve the same resultant RF phase shift. The vector representation of both (4) and (5) are pictorially illustrated in Fig. 2 in comparison with (2). The fundamental AC output from a square-law PD gives:

$$I_{\Omega_{RF}}(t,\Phi_{RF}) \propto 4AB\cos(\Omega_{RF}t+\Phi_{RF}) \tag{6}$$

Under the influence of the optical phase manipulation described in (4) or (5) on the DSB modulated optical signal, the relative optical phase change between the optical carriers and sidebands of $\Phi_{RF}$ has been coherently translated into the electrical domain as clearly described by (6). The analytical result presented here forms the essential foundation for the novel optical RF phase shifter employing optical phase manipulation and coherent detection being investigated in this paper. Two observations can be made from the analysis so far from (6). Firstly, the optical RF phase shifting in (6) is independent of the RF signal frequency, $\Omega_{RF}$. The optical RF phase shifting is therefore broadband in principle. It is potentially applicable for signals from 1-100 GHz and beyond. Secondly, there is no change in the output AC amplitude between (3) and (6). If the relative optical phase manipulation can be performed with optical phase shifters having constant optical insertion loss, then there will be no output amplitude-phase interdependency at the output PD.

It is worth noting that the analysis presented so far in this paper is applicable equally well to single-sideband (SSB) modulated optical signals. In fact, Stulemeijer *et al.* [26] presented results that could be considered as a SSB implementation.



*(a)*

*(b)*

Fig. 2. Vectorial representation of relative optical phase manipulation to achieve RF phase shifting from a DSB modulated optical signal using (a) Eq. (4) and (b) Eq. (5). Dashed lines represent Eq. (2). Clockwise direction is taken to be positive.

Recently, Yi *et al.* [28] demonstrated such SSB implementation for 10-20 GHz utilizing a programmable wavelength processor (PWP), which is a high-cost rack-mount device. The PWP-based solution has the ability to perform only static RF phase shifts. It has been stated that a good optical RF phase shifter design should have a capability of being modulated [11]. The optical RF phase shifter concept outlined in (4)-(6) only acts on the input DSB modulated optical signal, which implies that it can function unrestrictedly at any location in an RF photonic network similar to conventional RF phase shifters and thereby address the requirement of RF input-output separation. Furthermore, devices based on this optical RF phase shifter concept can be cascaded in principle without the need for repeated electro-optic conversion. This is the first time an optical RF phase shifting concept with such potential practicality has been proposed for standard DSB modulated optical signals.

### *A. Effect of Sideband Amplitude Imbalance*

To appreciate the effect of unequal sideband amplitudes, the upper sideband amplitude is set at $B \pm \Delta B$ giving an sideband amplitude imbalance of $\pm\Delta B$. This can occur due to wavelength-dependent attenuation. The DSB modulated optical field from (4) can be rewritten as:

$$\begin{aligned} E(t,\Phi_{RF}) = {} & Be^{j[(\omega_o - \Omega_{RF})t - \Phi_{RF}]} \\ & + Ae^{j\omega_o t} \\ & + (B \pm \Delta B)e^{j[(\omega_o + \Omega_{RF})t + \Phi_{RF}]} \end{aligned} \tag{7}$$

The fundamental AC component at the output of the square-law PD then becomes:

$$\begin{aligned} I_{\Omega_{RF}}(t,\Phi_{RF},\Delta B) \propto {} & (4AB \pm 2A\Delta B) \times \\ & \cos(\Omega_{RF}t + \Phi_{RF}) \end{aligned} \tag{8}$$

The sideband amplitude imbalance simply reflects a change in the AC amplitude at the output. For a given sideband amplitude imbalance of $\pm\Delta B$, the AC output amplitude is consequently affected by $\pm 2A\Delta B$. There is no resultant RF phase error.

### *B. Effect of Relative Optical Phase Imbalance*

The effect of unequal relative optical phase between the sidebands and carrier can be analyzed by setting the relative optical phase of the upper sideband in (4) to $\Phi_{RF} \pm \Delta\Phi_{RF}$, i.e. a relative sideband-carrier optical phase imbalance of $\pm\Delta\Phi_{RF}$ :

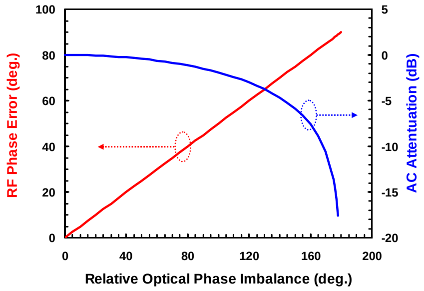


Fig. 3. RF phase error and AC amplitude attenuation as a function of the relative sideband-carrier optical phase imbalance from Eq. (10).

$$\begin{aligned} E(t,\Phi_{RF}) = {} & Be^{j[(\omega_o - \Omega_{RF})t - \Phi_{RF}]} \\ & + Ae^{j\omega_o t} \\ & + Be^{j[(\omega_o + \Omega_{RF})t + (\Phi_{RF} \pm \Delta\Phi_{RF})]} \end{aligned} \tag{9}$$

Similarly, the fundamental AC output can be derived:

$$\begin{aligned} & I_{\Omega_{RF}}(t,\Phi_{RF},\Delta\Phi_{RF}) \\ & \propto 4AB\cos\left(\Omega_{RF}t + \Phi_{RF} \pm \frac{\Delta\Phi_{RF}}{2}\right) \times \\ & \cos\left(\frac{\Delta\Phi_{RF}}{2}\right) \end{aligned} \tag{10}$$

The resultant RF phase shift error magnitude equates linearly to half of the relative sideband-carrier optical phase imbalance, i.e. $\pm\Delta\Phi_{RF}/2$. In addition, the AC amplitude at the output has also been attenuated by a factor of $\cos(\Delta\Phi_{RF}/2)$. Fig. 3 shows the expected RF phase shift error and AC amplitude attenuation as a function of the relative sideband-carrier optical phase imbalance. If the relative sideband-carrier optical phase imbalance can be conservatively managed to be less than ±20 degrees, then the expected RF phase error will be less than ±10 degrees and the AC amplitude attenuation will be negligible over a very wide electrical bandwidth. It is envisaged that much higher levels of optical phase control than ±20 degrees can be achievable with current optical phase shifter technology, e.g. electro-optic effect [26]. In comparison, a typical COTS 2-18 GHz digital RF phase shifter has RF phase and amplitude errors of ±20 degrees and ±3 dB, respectively. These errors are worsened for broader operating bandwidths.

### *C. Second-Order Harmonic Artifact*

The mixing of the lower and upper sideband components from (4) or (5) at the PD introduces a second-order harmonic artifact at the output of optical RF phase shifter regardless of $\Phi_{RF}$ being applied. The second-harmonic component can be derived:

$$I_{2\Omega_{RF}}(t,\Phi_{RF}) \propto 2B^2 \cos(2\Omega_{RF}t + 2\Phi_{RF}) \qquad (11)$$

The existence of the second-order harmonic artifact is undesirable, but it can be systemically managed by pre-determining the frequency operating bands and selecting appropriate PDs. The second-order harmonic artifact from this optical RF phase shifter can be minimized adequately by using 100-GHz PDs for 60-100 GHz band, 50-GHz PDs for 26-45 GHz band and 20-GHz PDs for 2-18 GHz band. In the final case, the second-order harmonic artifact will still be observed for signal frequencies from 2-10 GHz. Overall, it is possible to systemically manage the undesirable second-order harmonic artifact for 90% of signal frequencies from 1-100 GHz by simply selecting and matching PD bandwidths to the operating frequency bands.

## III. TOPOLOGY PROPOSAL

Fig. 4 shows a potential optical RF phase shifter architecture based on the theory presented in (4), which utilizes optical integrated cross-couplers and bandpass filters [29]-[34]. The lower sideband, carrier and upper sideband are first demultiplexed into individually components using integrated optical bandpass filters (OBPFs). Then the optical phase manipulation is performed. Optical phase shifter technology is readily available based on the electro-optic effect [26] as employed in all COTS EOMs. Ultralow dependence of the refractive index on wavelength (within the range of 1 nm) is essential. The multiplexing function in Fig. 4 is achieved by using the optical cross-couplers to combine the filtered and phase-shifted optical signals. The optical couplers and OBPFs can of course be replaced by suitable hyperfine wavelength demultiplexing technology.

The intention of the topology depicted in Fig. 4 is to focus on the optical RF phase shifting function to simplify the scope of the concept demonstration. The use of optical cross-couplers incurs an additional 3 dB loss per cross-coupler stage. However, their coherence is well known. Optical amplification is readily available to compensate for optical losses. It is also assumed that there is no optical phase difference through the integrated optical bandpass filters. This assumption is reasonable since any optical phase difference can be individually compensated for and equalized in practical devices by designing accurate optical waveguide lengths prior to the output combiner stage [29]. Since the optical RF phase shifter design presented in this paper is a coherent concept, the optical phase budget (in analogy to the optical power budget terminology) has to be analyzed to ensure that the architecture in Fig. 4 does operate in the manner intended to produce a phase-shifted RF output signal.

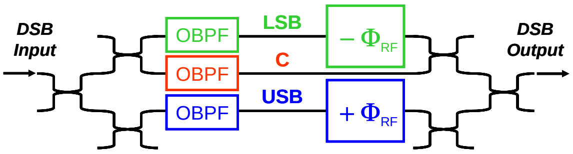


Fig. 4. A proposed optical RF phase shifter utilizing optical cross-couplers and bandpass filters. OBPF, optical bandpass filter; LSB, lower sideband; C, optical carrier and USB, upper sideband.

Fig. 5 summarizes the optical phase budget for the optical RF phase shifter from Fig. 4, which has two potential outputs for consideration and utilization. The vectorial representations of both outputs O1 and O2 relative to the optical carrier are illustrated in Fig. 6 for clarity.

Output O1 contains both lower and upper sidebands symmetrical with respect to the optical carrier. Output O1 can therefore be used to coherently produce a phase-shifted RF signal. The resultant fundamental AC output from output O1 is shifted by 180° when $\Phi_{RF} = 0^{\circ}$, while it experiences 0° phase shift when $\Phi_{RF} = 180^{\circ}$. This is an artifact of using optical cross-couplers to split and re-combine the DSB modulated optical signal.

The out-of-phase behavior can be corrected for by adding fixed optical 180° phase shifts after the optical bandpass filters for both the lower and upper sidebands. Simultaneously, output O2 produces a null RF output for all $\Phi_{RF}$. A quick analysis of the expected AC component at output O2 shows that the mixing of the lower sideband and carrier produces a signal that is *always* out-of-phase with that created by the upper sideband and carrier.

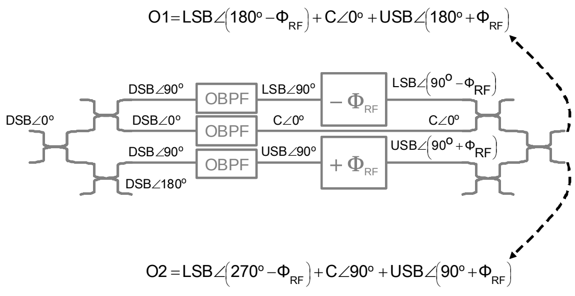
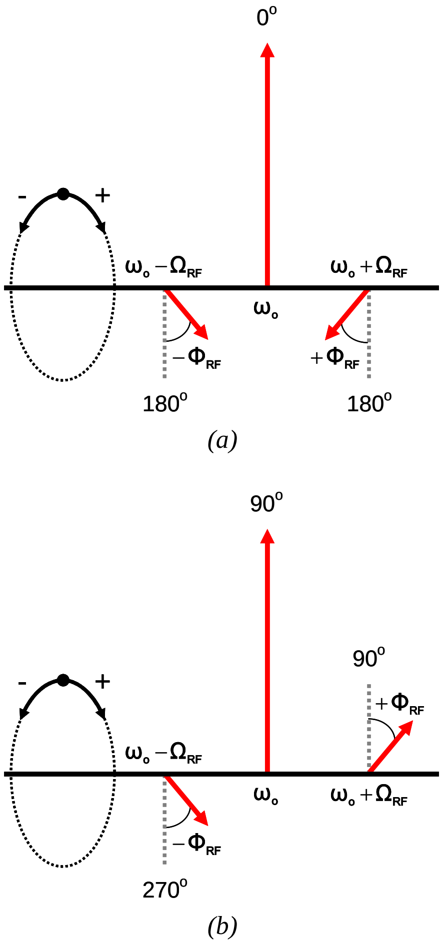


Fig. 5. Optical phase budget of the optical RF phase shifter in Fig. 4. OBPF, optical bandpass filter; LSB, lower sideband; C, optical carrier and USB, upper sideband.



*(a)*

*(b)*

Fig. 6. Output vectorial representation from the optical phase budget analysis of the uncorrected optical RF phase shifter in Fig. 4. Outputs (a) O1, and (b) O2.

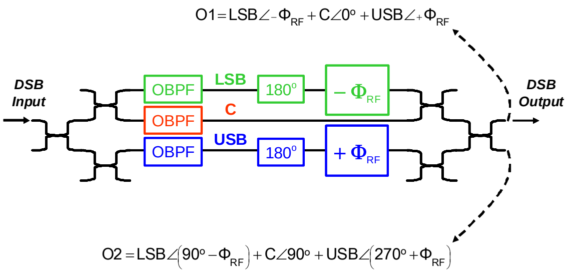


Fig. 7. Proposed phase-corrected optical RF phase shifter topology.

The phase-corrected optical RF phase shifter topology is shown in Fig. 7. This is the topology that will be numerically simulated and the results will be presented in a follow-up report.

## IV. DISCUSSION

In this paper, an optical RF phase shifting concept employing optical phase manipulation and coherent detection has been proposed. The theoretical analysis of the proposed optical RF phase shifting concept indicated that it is simple in principle. The proposed concept is a standalone sub-system in a similar manner to a conventional RF phase shifter. It has been shown qualitatively to have very low RF phase error and no output amplitude-phase interdependency. It also has the potential to address the systemic requirement of RF input-output separation that is often a missing consideration in the development of analogue RF photonic sub-systems and systems.

The architecture of the optical RF phase shifter proposed in this report lends itself to be implemented in photonic integrated circuitry. The material of choice to implement the optical RF phase shifter must have ultralow dependence of the refractive index on wavelength for electro-optic phase modulation. It must also be ideally immune to the operating environment to ensure that coherent detection. The most anticipated technical challenge would be the planar OBPFs, since optical cross-couplers and phase shifters can be readily fabricated. Nevertheless, it is hoped that the development of photonic integrated circuitry will be able to address this technical challenge in the near future.

The detailed numerical analysis and demonstration of the phase-corrected optical RF phase shifter topology as shown in Fig. 7, utilizing an industry-standard photonic simulator, will be presented in a follow-up paper in the same issue of this journal. A rigorous and thorough investigation will be discussed in reference to performance and design issues, which include linear phase responses over a frequency range of 10-50 GHz, various noise artifacts inherent in the design, and design trade-offs.

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