Optimization of Photonic Transmit/Receive Module Performance

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***Abstract*—Previous publications have described techniques that various researchers at Photonic Systems, Inc. and elsewhere have used to optimize the performance of analog photonic links. The success of these efforts has made the incorporation of antenna-remoting photonic links into radars and RF communications systems attractive to the designers of such systems. In this paper we show that the simple *addition* of photonic links to carry signals to and from an RF transmit/receive (Tx/Rx) module, while straightforward, is often not the most beneficial approach because it unnecessarily subjects the inherently broadband photonic components to the same bandwidth limitations as the RF circuitry in the module. If one instead begins with the idea that the broadband photonics technology should be *central* to the design of the antenna Tx/Rx interface, a completely new architecture emerges – one that not only has greater capabilities than the conventional RF interface, but is simpler as well. As an example of a photonics-based antenna interface design that is simple and yields improved capabilities, we present a Tx-Isolating Photonic Rx (TIPRX) link that operates over many octaves or even decades of bandwidth while providing 40 dB or more of isolation between the transmit and receive signals. The potential system impact of the TIPRX is that an antenna can receive low-power signals while simultaneously transmitting much higher-power signals.**

I. Introduction

The attractive characteristics of optical fibers – their small size and weight, immunity to electromagnetic interference, nearly negligible attenuation and dispersion, and tremendous RF bandwidth capacity – can make them more attractive than coaxial cables and other metallic waveguides as conveyors of RF signals over even moderate distances. The fibers' non-metallic make-up makes them an even more advantageous choice of conduit in applications where the signal conveyance is to and from an antenna. If such an antenna is meant to sense signals of small magnitude, it is important to boost the received signal amplitude using a low-noise amplifier (LNA) before the input to an analog photonic link unless this link has sufficiently low noise figure on its own [1].

The conventional approach to the design of a module permitting photonic remoting of the transmit (Tx) and receive (Rx) signals to and from an antenna interface is to simply add the necessary electrical-to-optical conversion hardware to the usual contents of a conventional Tx/Rx module. Fig. 1(a) shows a simplified block diagram of a conventional Tx/Rx module, and Fig. 1(b) shows this module with hardware added to permit photonic remoting of the RF signals. While photonic remoting reduces the size and weight of the RF feed cabling and permits other RF processing functions such as the formation and steering of wideband beams in a phased array of antenna elements, adding the required hardware as shown in Fig. 1(b) also increases the complexity and cost of the Tx/Rx module. Moreover, designing the module this way limits its bandwidth to that of the ferrite circulator, thereby subverting the inherently broader-band performance of the photonic remoting hardware.

The recent development of broadband photonic links that have low noise figure without any RF pre-amplification – e.g., < 6 dB across 6 – 12 GHz [2] and as low as 3.5 dB at 2 GHz [3] – has paved the way for the design of photonically remoted Tx/Rx modules without the limitations of the one shown in Fig. 1(b). This paper presents a novel Tx-Isolating Photonic Rx (TIPRX) link design that enables an antenna system to sense low-power signals over a broad bandwidth while effectively isolating the receivers from a signal being transmitted anywhere within this same broad range of RF frequencies [4].

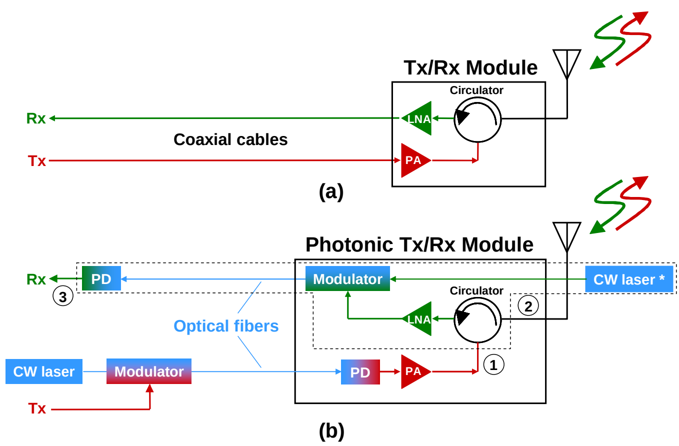

Fig. 1 (a) Conventional Tx/Rx antenna interface module. PA: power amplifier.
(b) Addition of photonic components to the conventional module to enable remoting of the Tx and Rx signals via optical fibers. The dashed box and port numbers are explained in Section II. *CW laser power can be delivered to the module via a third optical fiber.

This material is based in part upon work supported by DARPA under SSC-San Diego Contract N66001-04-C-8045. Any opinions, findings and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of DAPRA or SSC-San Diego.

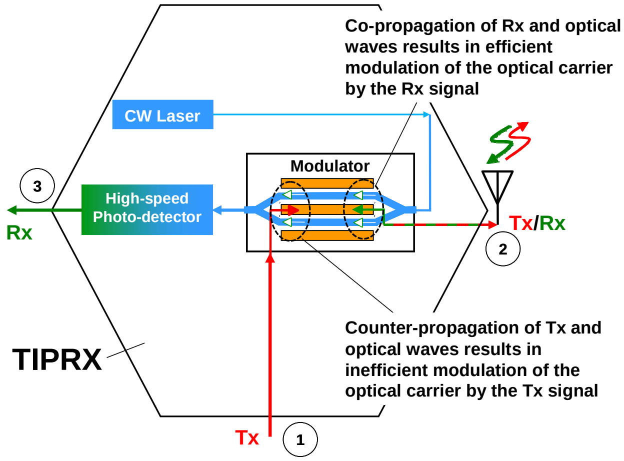

Fig. 2 Block diagram of the Transmit-Isolating Photonic Rx link (TIPRX). The three components inside the hexagon replace the five components inside the irregularly shaped dashed box shown in Fig. 1(b), with corresponding numbering of the three RF signal ports.

II. TIPRX Concept

The hexagon in Fig. 2 encloses the photonic hardware comprising the TIPRX. As is further explained at the end of this Section, the TIPRX performs all three of the functions performed by the hardware within the irregularly shaped dashed box of Fig. 1(b), and the RF port numbers in these two figures correspond exactly to one another. The Tx signal enters the TIPRX at RF port 1. At RF port 2 where it exits the TIPRX, the Rx signal enters and is routed to RF port 3.

The key component in the TIPRX is an electro-optic external modulator with traveling-wave electrodes. A laser supplies a CW optical carrier to one end of this modulator. An Rx signal of any RF frequency received by the antenna and fed into RF port 2 of the TIPRX *co-propagates* with this light along the entire length over which the two waves are made to interact in the modulator. Therefore the Rx signal modulates the light efficiently. A high-speed photodetector retrieves the Rx signal from the modulated optical output of the modulator, and directs it out of the TIPRX at RF port 3. To achieve the necessary Rx signal sensitivity does not require an LNA: as has been shown previously, proper design and implementation of a traveling-wave external modulator in an amplifierless link can yield suitably high gain and low noise figure over a broad range of RF frequencies [2, 3].

A Tx signal fed into RF port 1 of the TIPRX, by contrast, reaches the antenna connected to RF port 2 via the same set of modulator electrodes, but over a broad range of RF frequencies any Tx signal will be unable to modulate the light effectively because these two waves *counter-propagate* with respect to one another in the modulator. Therefore the receiver at RF port 3 is effectively isolated from Tx signals over much of the Rx link's broad bandwidth.

All in all, the TIPRX performs three functions in a Tx/Rx antenna remoting application:

1. *Like an LNA*, it amplifies the Rx signal with little added noise (i.e., low noise figure).
2. *Like an RF ferrite circulator*, it enables a bidirectional RF interface to the Tx/Rx antenna (but with greatly improved isolation over a broad range of frequencies, as is described in Sections III and IV of this paper).
3. *Like any other photonic link*, it takes advantage of the low-loss and low-dispersion characteristics of optical fibers to enable separation of the antenna and receivers by hundreds of meters or even several kilometers (with the maximum length depending on the maximum RF frequency). A photonic Tx/Rx module design based on the TIPRX is shown in Fig. 3, in which all TIPRX components other than the electro-optic modulator are shown along with the RF transmit signal generator and RF receiver at a location remote from the antenna.

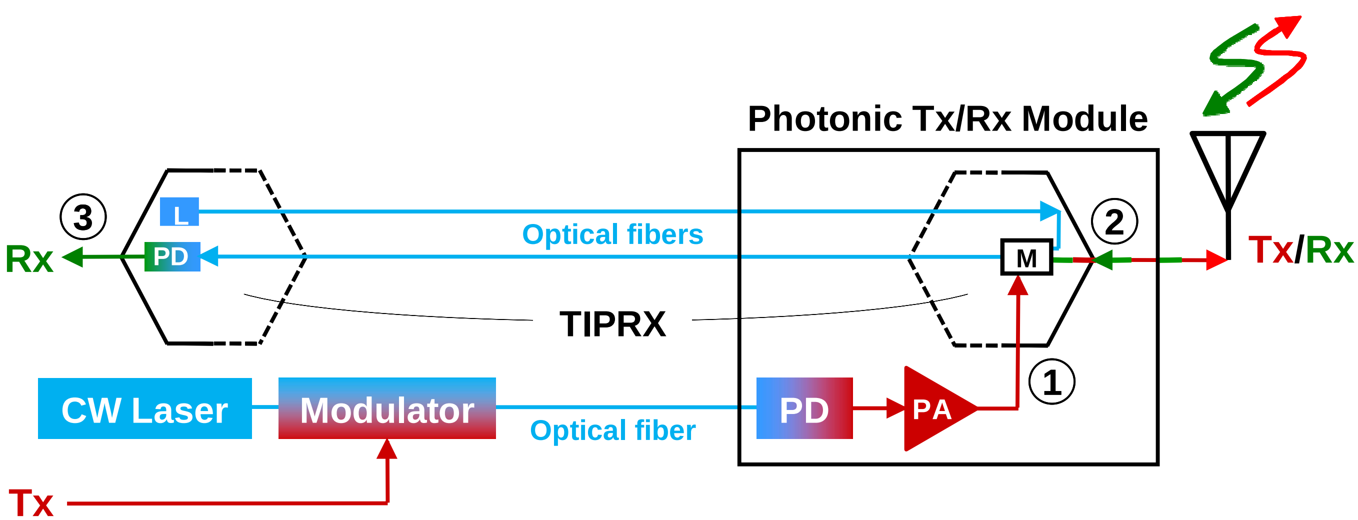

Fig. 3 Splitting apart of the TIPRX into the modulator portion at the antenna site and the CW laser and high-speed photodetector for the receive signal, both of which can be located at a remote site along with the Tx signal generator and the receiver for the Rx signal.

III. TIPRX MODEL

The RF performance of the TIPRX is characterized using all the usual RF figures of merit – i.e., the gain, noise figure, and dynamic range of the amplifierless photonic link that channels the Rx signal from the antenna to the receiver, and the RF insertion loss of the modulator electrodes that channel the Tx signal to the antenna – plus one additional parameter: the extent to which the TIPRX isolates the receiver from the Tx signal. Using the port numbering shown in Fig. 2, we refer to this figure of merit as the "port 1 – 3 isolation".

Models for the performance of the Rx signal channel through the TIPRX (port 2 to port 3) are well-established both theoretically and experimentally [1, 5], and the Tx signal channel (port 1 to port 2) can be modeled like any passive electrical transmission line with propagation constant $\gamma = \alpha + j\beta$. In this paper, therefore, we focus exclusively on the modeling of the port 1 – 3 isolation.

At any RF frequency, the port 1 – 3 isolation afforded by the TIPRX can be modeled using expressions that have been derived previously for the efficiency with which light is modulated in an electro-optic modulator by co- vs. counter-propagating RF signals on its traveling-wave electrodes [6]. The most accurate expression of isolation as a function of frequency is quite complex because it accounts for many imperfections in the modulator, including attenuation of the RF signal on the electrodes, imperfect matching of the RF signal's velocity on the electrodes to that of the light in the modulator's optical waveguides, and one or more points at which a portion of the RF signal is reflected because of an impedance mismatch. We are preparing a separate, longer, journal article that will include a more detailed model and will describe experiments that validate these details. In this paper, however, we neglect all of the above-mentioned imperfections in the modulator as second-order effects, which simplifies the expression for port 1 – 3 isolation to a great extent – i.e.,

$$Port\ 1-3\ Isolation \equiv \left|\frac{S_{31}}{S_{32}}\right|^2 = \frac{\sin^2(\beta_{RF} L)}{(\beta_{RF} L)^2}, \quad (1)$$

where L is the electrical-optical interaction length in the modulator, and where we have assumed perfect matching of the RF traveling-wave velocity v_{RF} to the optical wave's guided velocity v_{opt} in the device, such that

$$\beta_{RF} \equiv \frac{2\pi}{\lambda_{RF}} = \frac{2\pi\, f_{RF}}{v_{RF}} = \frac{2\pi\, f_{RF}}{v_{opt}} = \frac{2\pi\, f_{RF}\, n_{opt}}{c}. \quad (2)$$

Note from (1) and (2) that, in the limit as the RF frequency approaches dc and thus the distinction between co- and counter-propagating waves disappears, the port 1 – 3 isolation is defined such that it approaches unity (0 dB). As frequency increases, the isolation quickly improves, ostensibly reaching 0 ($-\infty$ dB) at the exact frequency for which its corresponding wavelength in the modulator's traveling-wave electrode structure is $2 \cdot L$. As dictated by (1) and (2), the port 1 – 3 isolation will hit similar optimal frequencies wherever an integer number of RF wavelengths fits exactly into $2 \cdot L$. In between these optimal frequencies, frequencies of worst-case port 1 – 3 isolation occur whenever an odd number of half wavelengths fits into $2 \cdot L$, with the worst-case isolation becoming more and more tolerable as this integer number continues to increase.

We performed an early proof-of-concept experiment to validate this simplified version of the model. Fig. 4 shows the measured port 1 – 3 isolation of a TIPRX that included a commercial off-the-shelf (COTS) traveling-wave modulator with an electro-optic interaction length of half an RF wavelength at f = 920 MHz. In the ratio of measured S-parameters displayed in Fig. 4, the effect of reflections due to RF impedance mismatches was negated by using the "gating" feature in the time-domain mode of the network analyzer to examine only the portion of the signal input at port 1 that reached port 3 after traversing the modulator electrodes once. With the effect of reflections negated, the resulting measured behavior closely resembles the "Model" curve in Fig. 4, which was generated by substituting into (1) the value of $\beta_{RF}L$ obtained by entering $c/2n_{opt}$ = 920 MHz$\cdot L$ into (2).

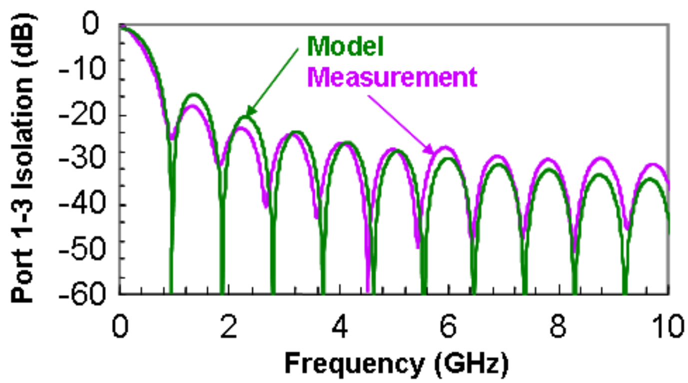

Fig. 4 Measured port 1 – 3 isolation of a TIPRX (magenta curve) with RF reflections "gated" out of the network analyzer measurements of S_{31} and S_{32} in an early experiment to validate the simple model (green curve) expressed in (1) and (2).

IV. MEASURED TIPRX PERFORMANCE

The time-domain gating technique we applied to the measured data shown in Fig. 4 for a COTS modulator-based TIPRX would not be a practical means of increasing the receiver's isolation from Tx signals in a real Tx/Rx antenna system. We have therefore developed a TIPRX in which we paid great attention to minimizing the deleterious effect of reflections in the modulator package over the frequency range at which we wished to operate. Because modulator manufacturers ordinarily have little reason to minimize these RF reflections – i.e., these reflections have little or no effect on the performance of a conventional photonic link – we had to depart somewhat from the "usual" modulator package design that gives rise to substantial opportunities for reflection of an RF signal.

The blue curve in Fig. 5 shows the measured 6 – 12 GHz port 1 – 3 isolation of a TIPRX designed in this way. Despite efforts to minimize their effect, residual RF reflections mask the characteristic shape predicted by (1) and evident in the data from the time-gated measurement shown in Fig. 4. Even in the face of these reflections, however, the TIPRX exhibited better than –35 dB of port 1 – 3 isolation across the entire 6 – 12 GHz frequency range, and better than –40 dB over one 1.7-GHz and a second 1.0-GHz wide portion of this band.

For comparison's sake, the measured port 1 – 3 isolation of the best COTS ferrite-based RF circulator available for this same frequency band is shown by the red curve in Fig. 5. Note that the TIPRX achieves better port 1 – 3 isolation at every frequency in the 6 – 12 GHz band.

Most COTS external modulators have input 1-dB compression powers in the neighborhood of +10 dBm (10 mW). Therefore there is little reason for the manufacturers of these devices to design them to withstand RF powers of 1 W or more. The electrodes of the TIPRX modulator, by contrast, must convey a Tx signal – ideally a very high-power Tx signal – to an antenna. Therefore, to satisfy ourselves that the modulator's traveling-wave electrode structure could support high-power RF Tx signals, we subjected one COTS modulator and one of our TIPRX modulators to large RF power levels in a controlled sequence known as a "step stress test". In this test an RF power of 1 W (at 1.7 GHz) was applied to port 1 of the TIPRX for 24 hours, then stepped up to 2 W for 24 hours. Before stepping up to 3 W for 24 hours, the input power was returned to 1 W for 24 hours. The test continued in this way, with a 24-hour interval at 1 W of input power before each subsequent upward step in input power. The temperature of the electrodes was monitored continuously throughout the test.

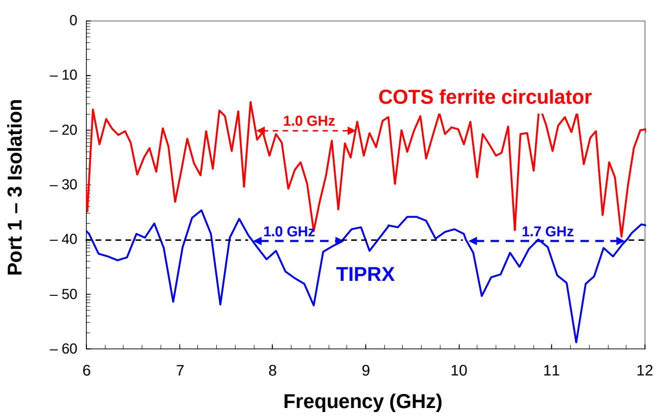

Fig. 5 Measured port 1 – 3 isolation of a TIPRX designed to minimize the deleterious effects of RF reflections at 6 – 12 GHz (blue curve). Better than –35 dB of port 1 – 3 isolation was achieved across the entire octave, and better than –40 dB of port 1 – 3 isolation was achieved across two bands of width 1.0 GHz and 1.7 GHz. The measured isolation for the best 6 – 12 GHz commercial ferrite-based RF circulator [7] is shown for comparison (red curve).

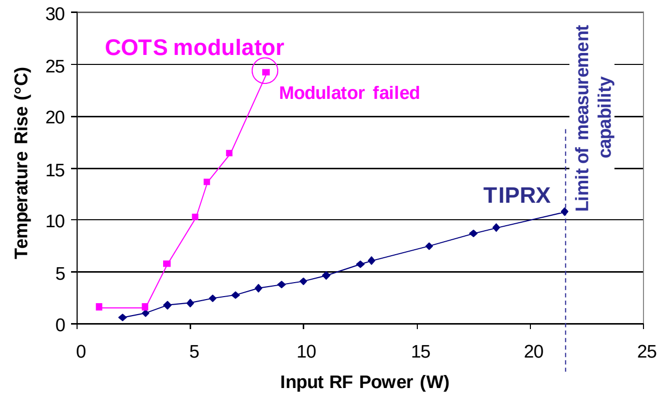

Fig. 6 Results of step stress tests, showing the TIPRX's improved RF power handling capability compared to that of a COTS modulator.

Fig. 6 shows the results of step stress testing of a COTS modulator and a modulator designed for our TIPRX to withstand greater Tx powers. Whereas the COTS modulator failed at an input power of ~ 8 W, the TIPRX withstood the maximum power that our test equipment was able to supply, which exceeded 20 W.

V. Summary and Conclusion

In summary, we have demonstrated that the amplifierless photonic links with low noise figure developed recently (e.g., [2], [3]) open the door to a completely new method of designing a photonically-remoted Tx/Rx module. In the novel architecture we call the Tx-Isolating Photonic Rx (TIPRX) link, a minimal set of broadband photonic components substitutes as the functional equivalent of an Rx-channel LNA, a fiber-optic link for analog signal remoting, and an RF ferrite circulator – but with greatly improved port 1 – 3 isolation over an octave-wide range of RF frequencies.

We conclude by pointing out that the performance of the TIPRX exceeds that of the hardware it replaces to such a significant extent that it enables an entirely new capability: *simultaneous* Tx/Rx operation of an antenna system.

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