# Photonics for Phased Array Systems

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**Abstract—***In the last several years, there have been significant advances in photonics for phased arrays. In this paper we present results in two key areas: 1) For receive-only arrays, we report on improvements in analog fiber links that have resulted in new records for the intrinsic noise figure – i.e. noise figure without any RF amplification – of less than 7.5 dB across 1 – 12 GHz and SFDR of 120 dB in a 1 Hz bandwidth; 2) For arrays that both transmit and receive, we report on a new type of link we call TIPRx, for transmit-isolating photonic receive link. This new type of link has significantly better T/R isolation than a ferrite circulator, and over a much wider bandwidth. It also has gain like an LNA and low noise figure. Hence a single TIPRx link is the functional equivalent of several individual RF components.*

## I. Introduction: Broad-bandwidth Receive-only Links with Low Intrinsic Noise Figure

In sensing systems that employ analog fiber-optic links for signal remoting, the noise figure of these links dictate the system's sensitivity to received signals. The demonstration of an intrinsic link — which we define as a link that uses no electronic amplifiers — that exhibits a broadband noise figure comparable to that of commercial broadband low-noise amplifiers (LNAs) has represented a "holy grail" for analog link designers. The external modulator in such a link can connect directly to a receiving antenna, and its optimum bias voltage can be maintained by a small circuit at this location that consumes only a few milliwatts of dc power. The other required link components — a high-power, low-relative-intensity-noise (low-*RIN*) optical source and a high-speed photodetector — can reside near the system receiver(s) for easier maintenance.

In this paper, we report the lowest measured noise figure for a broad-bandwidth 1 – 12 GHz intrinsic optical link and a measured spurious-free dynamic range (*SFDR*) that is correspondingly high but is limited by the low-biasing architecture to a suboctave portion of that potential 12:1 bandwidth. As has been reported previously, the devices used in this link can also be used in configurations suitable for multi-octave operation, such as the balanced detection architecture described in [1].

Figure 1 shows a block diagram of the link that we assembled for the purposes of this investigation. Figure 2 shows the gain and noise figure of the link shown in Fig. 1, measured at 1-GHz intervals between 1 and 12 GHz. We measured the gain shown by the blue points in Fig. 2 using an Agilent N5230A 4-port PNA Network Analyzer. Using a calibrated Agilent N8975A Noise Figure Analyzer, we also measured the noise figure shown by the red points in Fig. 2. To the author's knowledge, the measured noise figure of 3.4 dB at 2 GHz shown in this plot is the lowest ever reported for a broadband fiber-optic link without a pre-amplifier.

Fig. 3 shows the *SFDR* of the link, measured using a two-tone, third-order intermodulation distortion system designed by Photonic Systems, Inc. [2]. Error bars of ± 1 dB were deemed appropriate to the degree of uncertainty in measuring the low-power 3rd-order intermodulation distortion products.

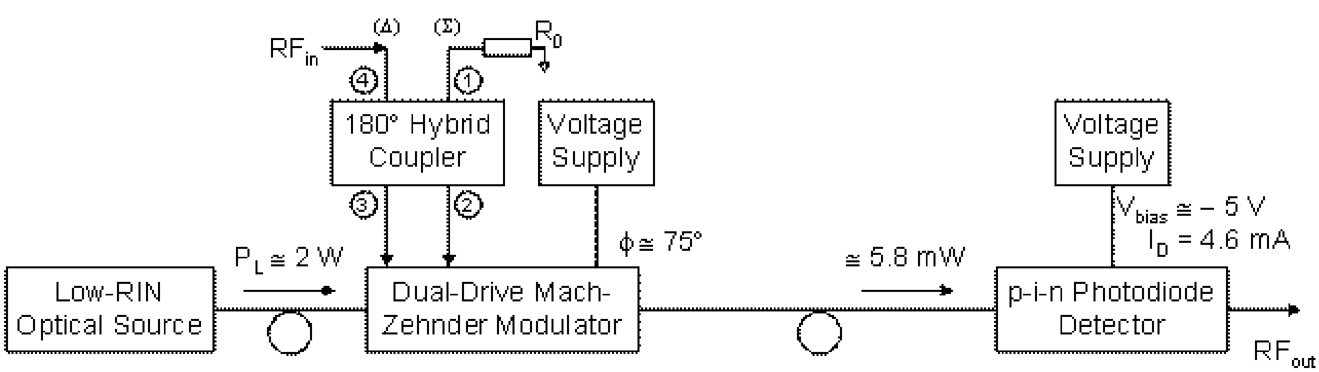


Figure 1 Block diagram of low noise figure, broad bandwidth optical link.

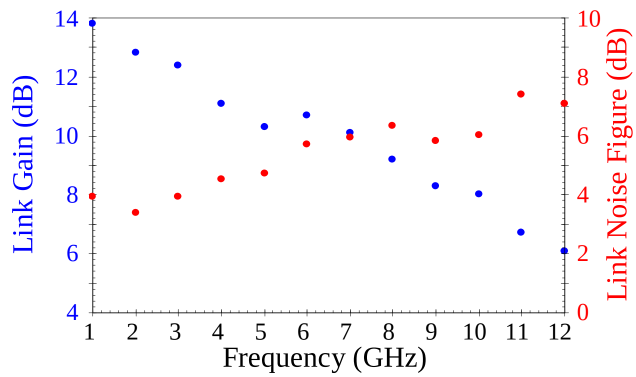


Figure 2 Measured gain and noise figure of link in Fig. 1.

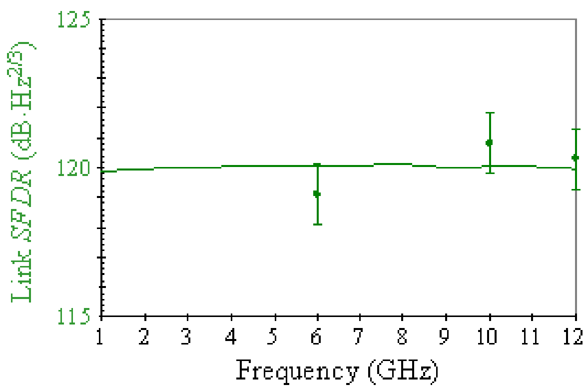


Figure 3 Measured (points) vs. modeled (line) spurious-free dynamic range (SFDR) of link in Fig. 1.

## II. TIPRx: A New Type of Link for Transmit and Receive Applications

The hexagon in Fig. 4 encloses the photonic hardware comprising the TIPRx link, which performs 3 functions:

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 Tx/Rx isolation over a broad range of frequencies).
3. *Like any other photonic link,* it exploits the low-loss and low-dispersion characteristics of optical fibers to enable separation of antennas 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 appears in Fig. 5, which shows all TIPRx components other than the electro-optic modulator situated along with the RF transmit signal generator and RF receiver at a location remote from the antenna.

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.

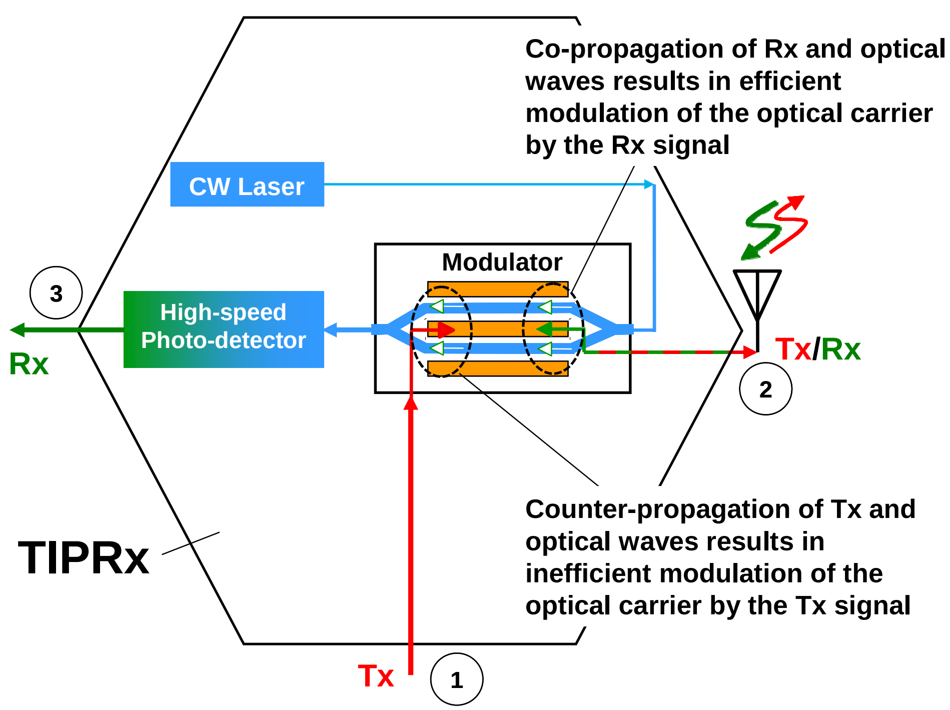


Figure 4 Block diagram of the transmit isolating photonic receive (TIPRx) showing the basis for enabling high Tx/Rx isolation.

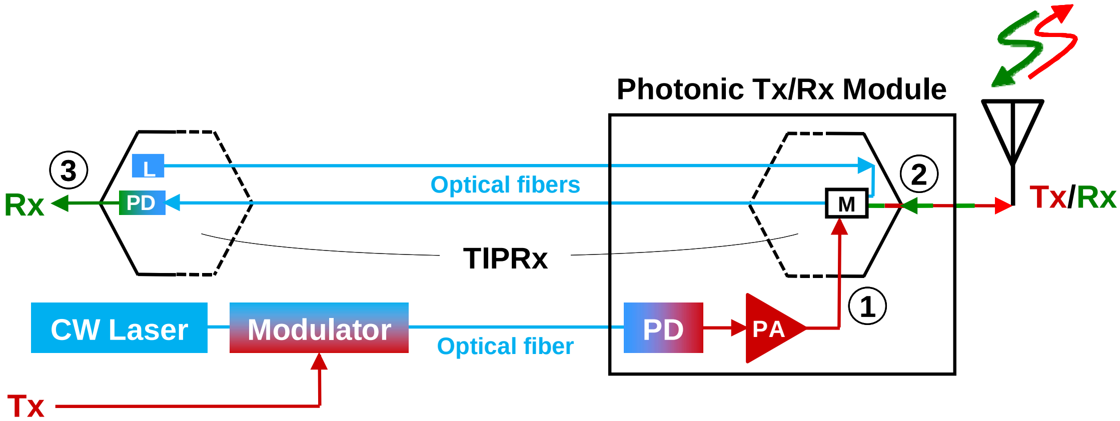


Figure 5 Splitting apart of the TIPRx into the modulator portion at the antenna site and the CW laser and high-speed photodetector for the Rx signal, which can both be located at a remote site along with the Tx signal generator and the receiver for the Rx signal.

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 link at RF port 3. To achieve the necessary Rx signal sensitivity does not require an LNA; as shown in Fig. 1, 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 [1 – 4].

A Tx signal fed into RF port 1 of the TIPRx link, 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.

We are preparing a separate, longer, journal article that will include a detailed TIPRx model and will describe experiments that validate these details. Here in this paper, however, we neglect imperfections in the modulator as second-order effects, which simplifies the expression for port 1 – 3 isolation to a great extent – i.e.,

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

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

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

We performed an early proof-of-concept experiment to validate this simplified version of the model. Fig. 6 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. 6, 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. 6, which was generated by substituting into (1) the value of $\beta_{RF}L$ obtained by entering $c/2n_{opt}$ = 920 MHz·$L$ into (2).

More recently we fabricated a modulator specifically intended for TIPRx operation. The blue curve in Fig. 7 shows the measured 6 – 12 GHz port 1 – 3 isolation of a TIPRx link 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. 6. Even in the face of these reflections, however, the TIPRx link 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-wide 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. 7. Note that the TIPRx link achieves better port 1 – 3 isolation at every frequency in the 6 – 12 GHz band.

## ACKNOWLEDGMENT

This material is based upon work supported by DARPA under SSC-San Diego Contract No. 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.

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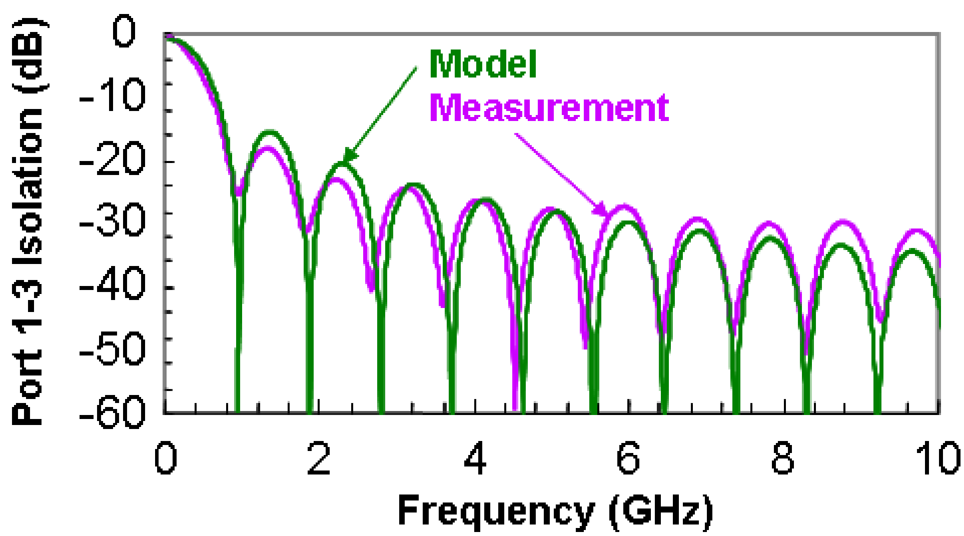


Figure 6 Measured port 1 – 3 isolation of a TIPRx (magenta curve) with RF reflections "gated" out of the network analyzer measurements of $S_{31}$ and $S_{32}$ in an early experiment to validate the simple model (green curve) expressed in (1) and (2).

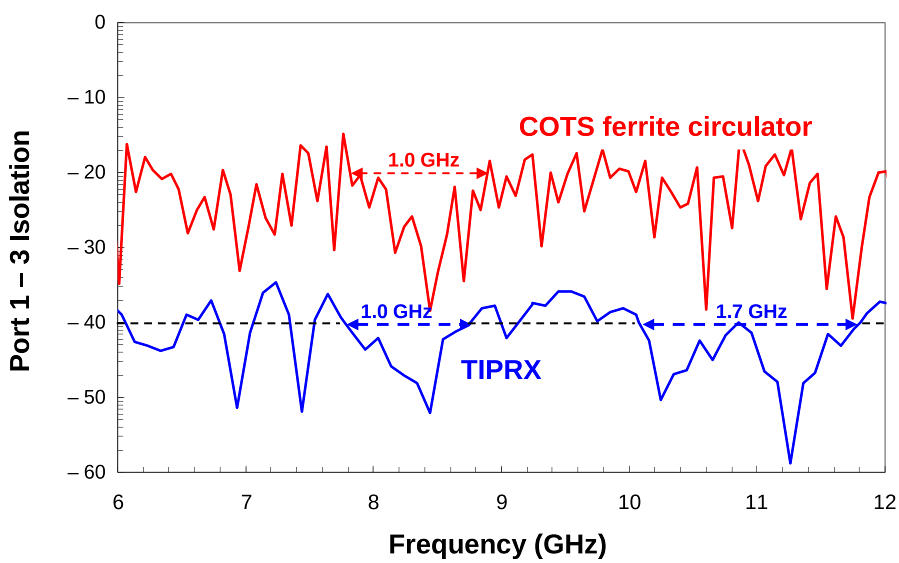


Figure 7 Measured port 1 – 3 isolation of a TIPRx link designed to minimize the deleterious effects of RF reflections at 6 – 12 GHz (blue curve). Better than –35 dB of port 1 – 3 isolation was achieved across the entire octave, and better than –40 dB of port 1 – 3 isolation was achieved across two bands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