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Wideband Adaptive Feedforward Linearized RF Photonic Link

S. R. O'Connor, T. R. Clark
Johns Hopkins University, Applied Physics Laboratory
Laurel, MD, USA
Sean.OConnor@jhuapl.edu

D. Novak
Pharad, LLC; Glen Burnie, MD, USA
ARC Special Research Centre for Ultra-Broadband Information Networks, The Univ of Melbourne, Australia

***Abstract*— We present new experimental data of the first multi-band adaptive feedforward linearized RF photonic link. Adaptive feedforward third order correction of 18 – 24 dB and SFDR values > 110 dB-Hz$^{2/3}$ over a multi-band operating bandwidth (S through Ku) with instantaneous bandwidths approaching 1 GHz, are demonstrated. Similar linearity performance is also demonstrated under pulsed operation of the wideband adaptive linearized RF photonic link.**

I. Introduction

The low-loss, electromagnetic interference free, and wide bandwidth signal transport of optical fiber, offers the potential for providing new capabilities, significant performance improvements, and design flexibility to a diverse range of RF and microwave systems. These applications include fiber-optic antenna remoting in RF sensor systems and commercial wireless telecommunication networks. The high dynamic range targets of many of these applications however present a major hurdle to fully realizing the benefits of fiber networks in microwave systems due to the inherent nonlinearity of the electrical-to-optical (E/O) conversion process.

A number of techniques for correcting microwave photonic link nonlinearities have been reported including novel electro-optical modulator designs [1] and linearization schemes [2 – 6]. Most linearization schemes suitable for RF photonic links are derived from common RF amplifier design techniques and include predistortion [2, 3] and feedforward (FF) [4 – 6] architectures. A key challenge associated with the implementation of linearized RF photonic links is achieving both high spurious free dynamic range (SFDR) and large operational and/or instantaneous bandwidths. Previous implementations of FF linearized photonic links have been limited to frequencies < 6 GHz while the operating frequency of adaptive predistortion circuits for photonic transmitters was limited to < 2 GHz with SFDR < 100 dB-Hz$^{2/3}$.

Recently, we proposed and presented the first demonstration of a wideband high dynamic range RF photonic link incorporating feedforward linearization and also featuring adaptive functionality [7, 8]. We presented measurements of the linearity performance of the FF linearized RF photonic link that demonstrated a multi-octave operational bandwidth and a SFDR approaching 120 dB-Hz$^{2/3}$ under manual control of the proof of concept system [8]. We also demonstrated the operation of the wideband FF linearized RF photonic link in a traffic-carrying mixed data wavelength division multiplexed fiber network [7].

We have furthered our experimental investigation of the wideband adaptive FF linearized RF photonic link and present the new data here. Our demonstration system has been extended to now operate completely autonomously. In this paper we quantify the SFDR performance of this stand-alone circuit under adaptive operation over a 1 – 20 GHz frequency range for instantaneous bandwidths extending up to 1 GHz. We also present the results of a preliminary investigation into the performance of the adaptive RF photonic link under pulsed operation.

II. Adaptive Feedforward Linearization

Our approach for correcting the performance limiting E/O nonlinear distortion in RF photonic links is based on the use of feedforward linearization. Control loops are utilized in our architecture to provide real-time adaptive capability whereby the circuit can maintain system performance during changing operating conditions that arise due to variations in input signal, environmental changes, component parameter tolerances, and device aging.

Figure 1 shows the architecture of the wideband adaptive FF linearized RF photonic circuit. The circuit is based on an intensity modulation direct detection link, where an electro-optic modulator (EOM) encodes the input RF signal(s) with a sinusoidal transfer function. Distortion due to this nonlinear transfer function is dominated by third-order intermodulation distortion products (IMD3) which are important to suppress since they typically lie within the frequency band of interest. As shown in Figure 1, the experimental set-up includes three circuits: signal cancellation circuit (SCC), error cancellation circuit (ECC), and control circuit (CC), to provide the link with adaptive capability.

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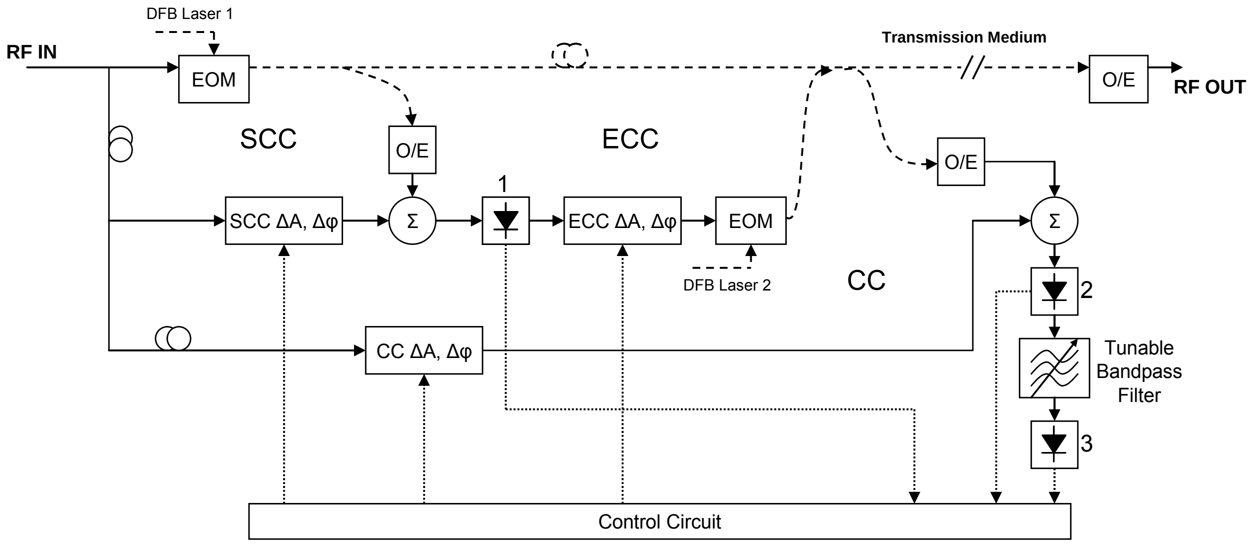

Figure 1. Schematic of wideband adaptive feedforward linearized RF photonic circuit

As their names imply, the SCC and ECC in the circuit shown in Figure 1 cancel the signal and error respectively, forming the foundation of a conventional feedforward linearization system. The input RF signal to the FF linearized RF photonic circuit is split into three paths. In the SCC, the amplitude and phase of one of the copies of the input signal (represented by the 'ΔA, Δφ' block) is adjusted for maximum signal cancellation when it is combined with a portion of the main optical path after optical-to-electrical (O/E) conversion. The main optical signal and the input RF replica are arranged to have equal amplitudes and be anti-phase when combined; the signal component is then cancelled leaving only the error. The error signal is then prepared by amplitude and phase adjustment and encoded with a second EOM in the ECC before being optically coupled back into the main transmission path. Proper error cancellation occurs when these two signals are equal in amplitude and opposite in phase and ideally, an undistorted copy of the input RF signal through the transmission medium at the final O/E conversion will result.

The CC in the adaptive FF linearized RF photonic link is effectively a signal cancellation loop that monitors the performance of the circuit. It operates in a similar way to the SCC; combining the amplitude and phase adjusted section of the undistorted input RF signal and a fraction of the transmitter output to isolate the remaining distortion component of the output signal.

The operating bandwidth of the circuit shown in Figure 1 is dependent only on the frequency response of the components and the path length difference of the delay lines at the signal and error combination points. In implementing the wideband adaptive FF linearized photonic link, appropriate commercial-off-the-shelf devices were used to realize a multi-band operational bandwidth. The primary photonic link comprises an 80 mW distributed feedback (DFB) semiconductor laser, a $LiNbO_3$ EOM, and a PIN photodiode receiver. A second photonic link constituting the ECC utilizes a separate 40 mW DFB laser, an identical EOM and shares the photoreceiver, where the distortion cancellation occurs, with the primary photonic link.

Each control loop in Figure 1 includes a RF vector modulator to provide amplitude and phase tuning as well as a wideband RF detector (the numbered diode blocks in Fig. 1) to provide feedback on the loop performance. The detectors provide a voltage proportional to the RF signal strength at their specific locations with detectors 1 and 2 monitoring the signal cancellation in the SCC and CC, respectively, and detector 3 (along with the tunable bandpass filter) monitoring the error cancellation regulated by the ECC loop. A control circuit interfaces between the various components in the control loops and also executes the control algorithms that provide adaptive functionality in the FF linearized photonic link. Further information regarding the adaptive algorithms can be found in [7, 8].

III. EXPERIMENTAL RESULTS

The linearity performance of the adaptive FF linearized photonic circuit was measured over the RF component limited operational bandwidth of 1 – 20 GHz. Fundamental and IMD3 levels were measured using a 40 GHz RF spectrum analyzer. Figure 2 shows examples of the measured IMD3 suppression performance for test signals comprising a two-tone RF signal centered at 6.5 GHz, 10 GHz and 15 GHz with a 10 MHz frequency separation. Each of the figures shows the measured RF spectra of the detected optical output signal without FF linearization and with adaptive FF linearization implemented. As can be seen from the results, 20 – 25 dB suppression of third order intermodulation distortion products in a 30 MHz instantaneous bandwidth (IBW) were able to be achieved with the adaptive FF linearized circuit.

The SFDR of the wideband adaptive FF linearized RF photonic link was determined from the IMD3 suppression measurements and the measured noise floor of the system, which was consistent with that expected for a photocurrent of ~ 3.13 mA. Table I summarizes the measured SFDR performance of the link at IBWs of 30 MHz and 300 MHz.

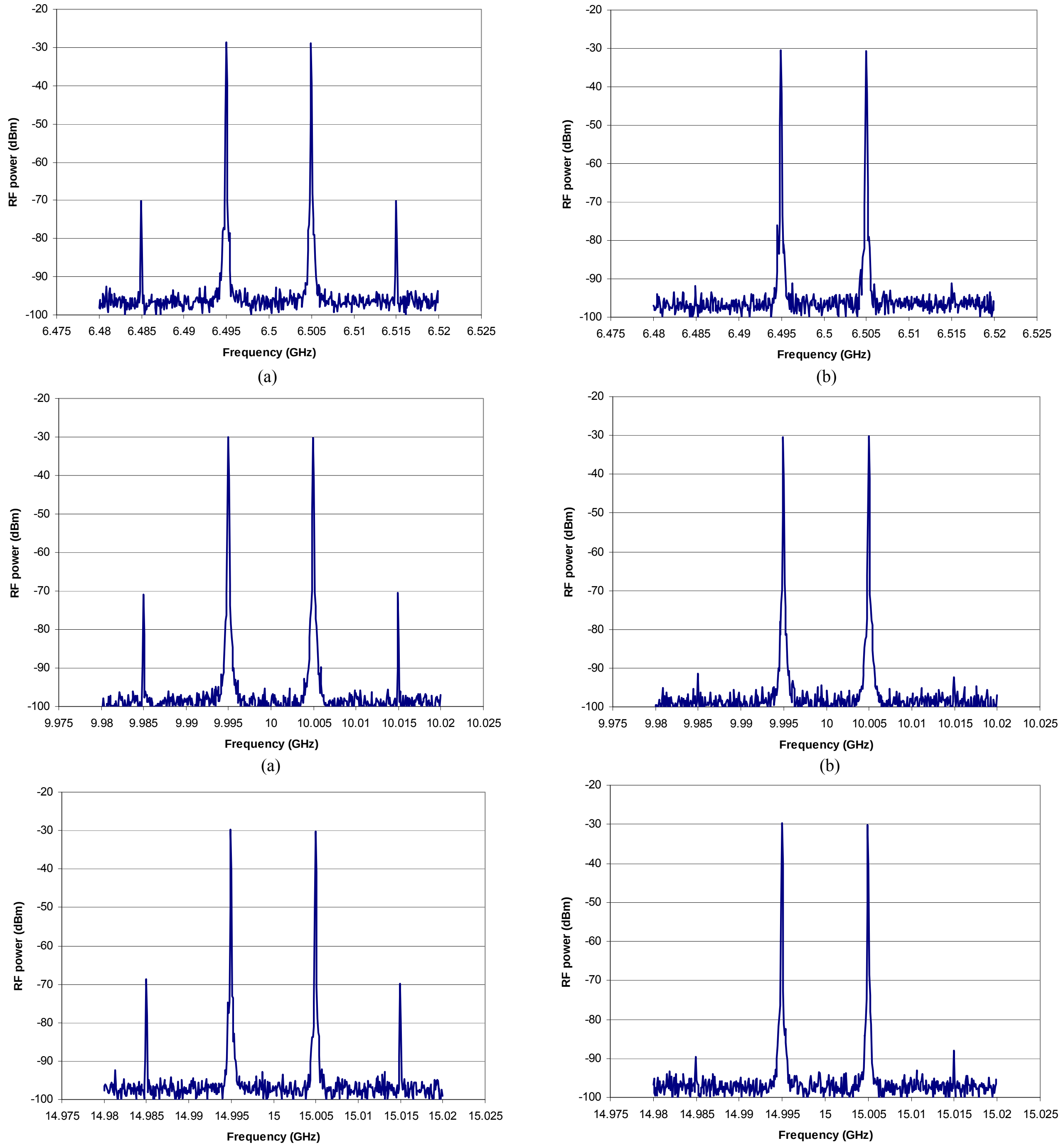

Figure 2. Measured IMD3 suppression of the wideband RF photonic link: (a) without and (b) with adaptive FF linearization at 6.5 GHz (top), 10 GHz (middle), and 15 GHz (bottom) with 10 MHz two-tone spacing

TABLE I. MEASURED SFDR OF ADAPTIVE FF LINEARIZED RF PHOTONIC LINK

Center Frequency (GHz)	SFDR (dB-Hz$^{2/3}$)	
	30 MHz IBW	**300 MHz IBW**
3	112.97	111.86
6.5	111.76	111.90
10	114.03	111.16
15	115.24	111.07

As can be seen in Table I, for a 30 MHz IBW the SFDR of the adaptive FF linearized RF photonic link varied from 113 to > 115 dB-Hz$^{2/3}$ across the multi-octave operating band. SFDRs exceeding 110 dB-Hz$^{2/3}$ were also achieved for a 300 MHz instantaneous bandwidth. These values represent an improvement in SFDR performance provided by adaptive FF linearization of approximately 6 – 8 dB-Hz$^{2/3}$ compared to no linearization in the wideband RF photonic link.

We also investigated the linearity performance of the wideband adaptive FF linearized RF photonic link at larger instantaneous bandwidths. Table II shows the measured SFDR performance at a center frequency of 10 GHz for IBWs ranging from 3 – 900 MHz. SFDR values in excess of 110 dB-Hz$^{2/3}$ were obtained for IBWs approaching 1 GHz, demonstrating that the adaptive FF circuit can achieve good linearity over significant instantaneous bandwidths.

TABLE II. MEASURED SFDR OF ADAPTIVE FF LINEARIZED RF PHOTONIC LINK AT 10 GHZ FOR DIFFERENT IBWS

Instantaneous Bandwidth (MHz)	**SFDR (dB-Hz$^{2/3}$)**
3	113.91
30	114.03
150	113.81
300	111.16
600	113.10
900	111.40

IV. PULSED OPERATION

We carried out a preliminary investigation of the linearity performance of the wideband adaptive feedforward linearzied RF photonic link under pulsed operation. In this test, a pulsed X-band (10 GHz) carrier at a 10 kHz repetition rate and 50 % duty cycle was input to the adaptive RF photonic link. A continuous wave signal was also introduced at a frequency offset from the pulsed carrier of 1 MHz to create in-band intermodulation distortion.

Figures 3(a) and (b) show the measured RF spectra of the detected optical output of the link without and with adaptive FF linearization implemented, respectively. The pulsed carrier, exhibiting the triangular spectrum expected for square wave pulsed carrier operation, and the unpulsed interferer signal can be seen with IMD3 products also clearly present in Figure 3(a). With adaptive FF linearization implemented however, the distortion products are suppressed. Figure 3(b) demonstrates that more than 20 dB IMD3 suppression was achieved under pulsed operation of the wideband RF photonic link.

V. CONCLUSIONS

We have presented new experimental data of the first wideband, multi-octave RF photonic link featuring feedforward linearization and adaptive functionality. Measured SFDR values greater than 110 dB-Hz$^{2/3}$ have been demonstrated across the multi-band operational bandwidth with instantaneous bandwidths approaching 1 GHz, for the RF photonic link operating completely autonomously and suppressing IMD3 products in real-time. Similar linearity performance was also demonstrated under pulsed operation of the wideband adaptive FF linearized RF photonic link.

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REFERENCES

[1] P. Liu, B. Li, and Y. Tirson, "In search of a linear electrooptic amplitude modulator", *IEEE Photon. Technol. Lett.,* vol. 3, pp. 144–146, 1991.

[2] G. Steiner, S. Hunziker, and W. Baechtold, "Reduction of 3rd order intermodulation of a semiconductor laser by an adaptive low-cost predistortion circuit at 1.8 GHz", *Proc. LEOS Summer Top. Meet.,* San Diego, CA, pp. 43–44, 1999..

[3] R. Sadhwani and B. Jalali, "Adaptive CMOS predistortion linearizer for fiber-optic links", *IEEE J. Lightw. Technol.,* vol. 21, pp. 3180–3193, 2003.

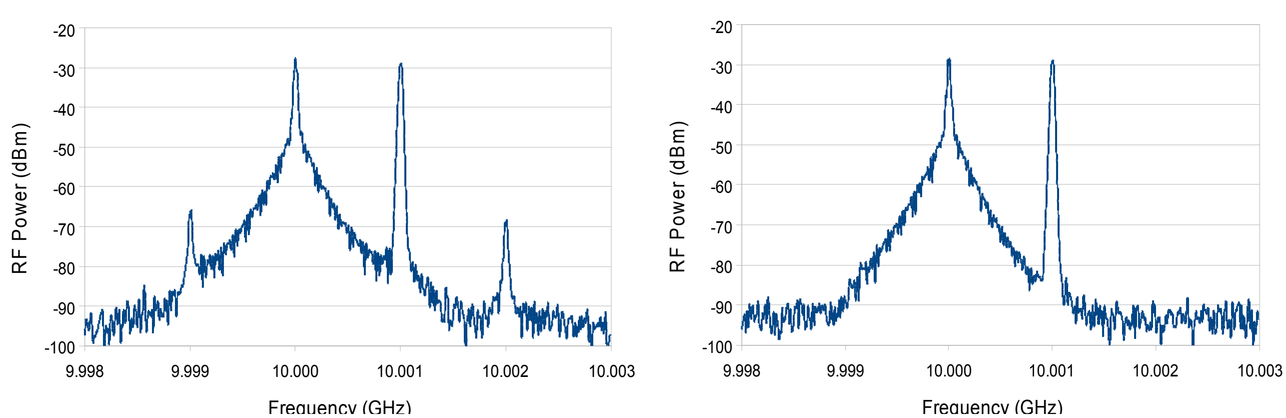
[4] R. M. de Ridder and S. K. Korotky, "Feedforward compensation of integrated optic modulator distortion," *Proc. Opt. Fiber Commun. Conf. (OFC),* p. 78, 1990.

[5] J. D. Farina, B. R. Higgins, and J. P. Farina, "New linearization technique for analog fiber-optic links", *Proc. OFC,* pp. 283–285, 1996.

[6] S. H. Park and Y. W. Choi, "Significant suppression of the third intermodulation distortion in transmission system with optical feedforward linearized modulator," *IEEE Photon. Technol. Lett.,* vol. 17, no. 6, pp. 1280–1282, 2005.

[7] D. Novak and T. R. Clark, "Broadband adaptive feedforward photonic linearization for high dynamic range signal remoting," *Proc. IEEE Military Commun. Conf.,* Orlando, FL, Oct. 2007.

[8] S. R. O'Connor, T. R. Clark, and D. Novak, "Wideband adaptive feedforward photonic link", to appear in *J. Lightw. Technol.,* Aug. 2008.



(a) (b)

Figure 3. Pulsed testing of the adaptive RF photonic link: Measured RF spectra (a) without, and (b) with feedforward linearization