Analog Performance of an Ultrafast Sampled-Time All-Optical Fiber XPM Wavelength Converter

Lavanya Rau, *Student Member, IEEE*, Roopesh Doshi, *Student Member, IEEE*, Suresh Rangarajan, *Student Member, IEEE*, Yijen Chiu, Daniel J. Blumenthal, *Fellow, IEEE*, and J. E. Bowers, *Fellow, IEEE*

***Abstract*—Analog performance of an all-optical ultrafast wavelength converter is measured and reported for the first time. The wavelength-conversion process is based on nonlinear cross-phase modulation in an optical fiber combined with an optical filter to convert phase modulation to amplitude modulation. The spurious-free dynamic range (SFDR) of the converter is measured to be 82 dB $\cdot$ Hz$^{2/3}$. We define a new metric called the SFDR power penalty, which measures the degradation in SFDR relative to baseline the back-to-back analog optical link. The SFDR power penalty was measured to be 5 dB $\cdot$ Hz$^{2/3}$ and is shown to be a function of the input optical power. This metric is used to characterize the linear region of the optical wavelength converter.**

***Index Terms*—Analog systems, spurious-free dynamic range (SFDR), wavelength conversion.**

I. Introduction

Ultrafast fiber wavelength converters have been successfully used to switch high-speed digital information for optical networks at rates beyond 80 Gb/s [1]; however, little has been reported on their use in analog systems. The extremely high instantaneous bandwidth of these wavelength converters can be used to realize wavelength switching for high-frequency analog radio frequency (RF) systems. New applications in analog RF systems, including switching or routing through an optical network and beam steering of analog signals using wavelength, may be possible. Certain analog applications like optical analog-to-digital (A/D) converters [2]–[4] require high-speed sampling with the performance requirements of analog RF systems including high linearity and dynamic range.

In this letter, we report for what we believe is the first time, the measured analog performance of an all-optical wavelength converter. The wavelength converter is based on cross-phase modulation (XPM) in nonlinear optical fiber [5]. The incoming data signal introduces a phase shift on the local continuous-wave (CW) signal through the fiber nonlinearity. The phase shift translates to a frequency shift of the CW light and produces spectral sidebands in the CW light. The wavelength-converted data can be recovered by filtering one of these sidebands. The efficiency of conversion is directly proportional to the nonlinear coefficient of the fiber, derivative of the incoming data signal and the length of the fiber. The wavelength-conversion process is more efficient for amplitude-modulated pulses rather than amplitude-modulated CW light. In this work, we employ short optical pulses to sample the analog signal before wavelength conversion in order to maximize the wavelength-conversion efficiency. The performance of the wavelength converter for sampled analog signal is important for applications such as demultiplexing high-speed samples to lower rates or for applications such as beam steering. We have measured a spurious-free dynamic range (SFDR) of 82 dB $\cdot$ Hz$^{2/3}$ and define a new metric called the SFDR penalty to quantify analog signal degradation associated with the wavelength converter. The SFDR penalty of the fiber XPM wavelength converter was measured to be 5 dB $\cdot$ Hz$^{2/3}$.

Manuscript received August 20, 2002; revised December 12, 2002. This work was supported by DARPA COAST under Award N66001-98-I-8925.

The authors are with the Department of Electrical and Computer Engineering, University of California, Santa Barbara, CA 93106 USA (e-mail: lgrau@engineering.ucsb.edu).

Digital Object Identifier 10.1109/LPT.2003.809260

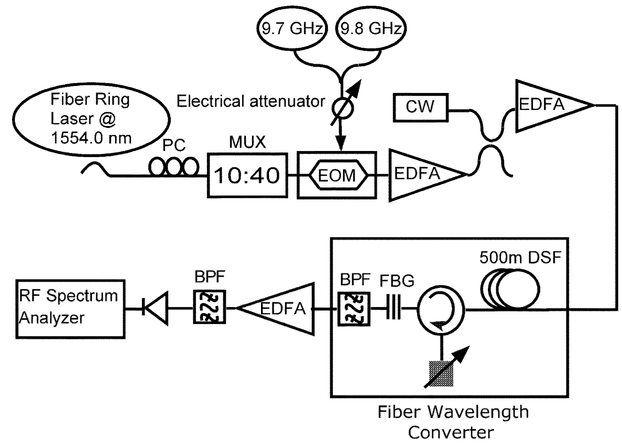

Fig. 1. SFDR measurement setup.

II. Wavelength Converter Architecture

The wavelength-converter architecture is illustrated in Fig. 1 and is described in more detail in [5]. Wavelength conversion is based on the principle of XPM induced by differential signals in a length of nonlinear fiber, such as a dispersion-shifted fiber (DSF) or a highly nonlinear fiber. A CW signal or a pulse train at a new wavelength λ_j is combined with an intensity modulated pulse train at wavelength λ_i. The incoming data imposes a phase modulation of the CW signal or the pulse train due to XPM. This phase modulation causes a spectral broadening of the CW signal or the pulse train thereby generating sidebands, as shown by the inset in Fig. 1. A circulator/fiber Bragg grating (FBG) arrangement is used after the DSF to notch out the original data signal. This is followed by a tunable bandpass filter to filter out one of the sidebands of the CW light. The filtering of one of the sidebands converts phase modulation to amplitude modulation. This method of wavelength conversion is in principle very fast (> 100 Gb/s) since nonlinear fiber processes are almost instantaneous. The wavelength converter acts as a digital 2R regenerator when operated in its nonlinear regime. Analog operation is achieved when operated in the linear regime.

III. SFDR Measurement Setup and Procedure

A two-tone approach was used to measure the SFDR of the wavelength converter, as shown in Fig. 1. Since the wavelength converter operates differentially, the two RF tones were sampled with a 40-GHz transform-limited [7-ps full-width at half-maximum (FWHM)] optical pulse train at 1554.0 nm, that was generated from an actively mode-locked fiber ring laser. An electrooptic modulator with a V_π of 4.0 V was used to amplitude modulate the optical pulse train with a composite electrical signal consisting of 9.7- and 9.8-GHz tones. This optically sampled two-tone signal was then wavelength converted to 1548.0 nm using the nonlinear XPM technique described in the previous section. For this particular measurement, we used 500 m of DSF as the nonlinear medium. A circulator and FBG arrangement was used at the output of the DSF to notch out the CW part of the wavelength converted signal and transmit the spectrally broadened part. The notched out light was reflected by the FBG and dumped at the output of the circulator, as shown in Fig. 1. A tunable bandpass filter of 0.4 nm is used to filter the spectrally broadened part and convert the phase modulation to amplitude modulation. To measure the SFDR, the sampled signal before and after wavelength conversion was detected by a wide-band photoreceiver, which included a 10-GHz electrical low-pass filter. The average optical power input to the photoreceiver was kept constant at -8 dbm, so as not drive it into saturation. The received electrical signal from the photoreceiver was input to the RF spectrum analyzer to measure the SFDR of the system with and without the wavelength converter. When a composite electrical signal containing the two tones f_1 and f_2 ($f_1 \approx f_2$) is optically sampled by a pulse train of frequency f_S ($f_S \approx 4f_1$), the electrical tones observed in a 1-GHz bandwidth around f_1 would be f_1, f_2 ($2f_2 - f_1$), ($2f_1 - f_2$), ($f_S - 2f_1 - f_2$), and ($f_S - 2f_2 - f_1$). In this letter, we limit our attention to the third-order mixing terms. The 40-GHz optical sampling pulse train we used was generated by passive multiplexing of a 10-GHz pulse train; thus, in addition to the above listed electrical tones, we also observed tones at frequencies $f_S/4$, ($2f_S/4 - f_1$), and ($2f_S/4 - f_2$). This can be confirmed from the electrical spectrum in Fig. 2. The SFDR is defined as the range between the noise floor and the level at which the third-order intermodulation (IMD) products are tangential with the noise level. To measure the SFDR of the link, the RF driving power to the electrooptic modulator is varied in steps of 1 dB. The power in the first- and third-order IMD terms is measured with the RF spectrum analyzer at the output of the link after photodetection. Fig. 3 shows the plot of the power in the first and third IMD tone versus the input electrical power. As expected, the first- and third-order IMD terms have slopes of 1 and 3, respectively. The linear curves are then extrapolated to intersect the noise floor. The SFDR is then measured as the difference in the output power of the primary tone and the power in the third-order IMD tone, when the third-order IMD tone is equal to the noise floor. In our system, the electrical spectrum analyzer limited the noise floor to -130 dBm, when measured with a 30-Hz resolution bandwidth.

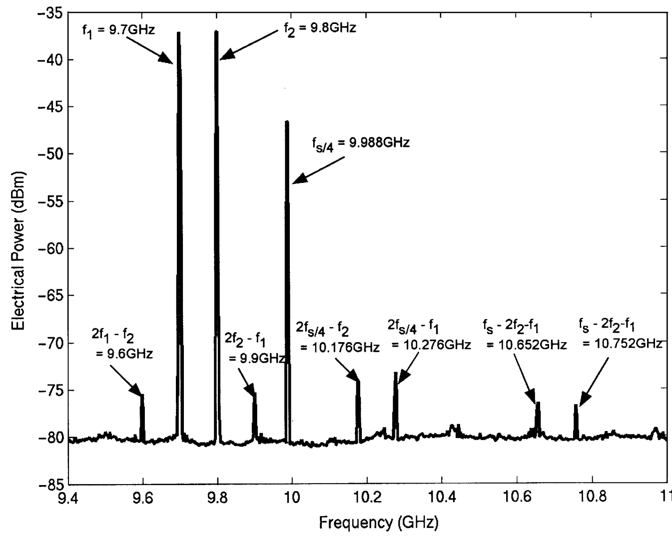

Fig. 2. Example measured RF power spectra for time sampled two-tone signal.

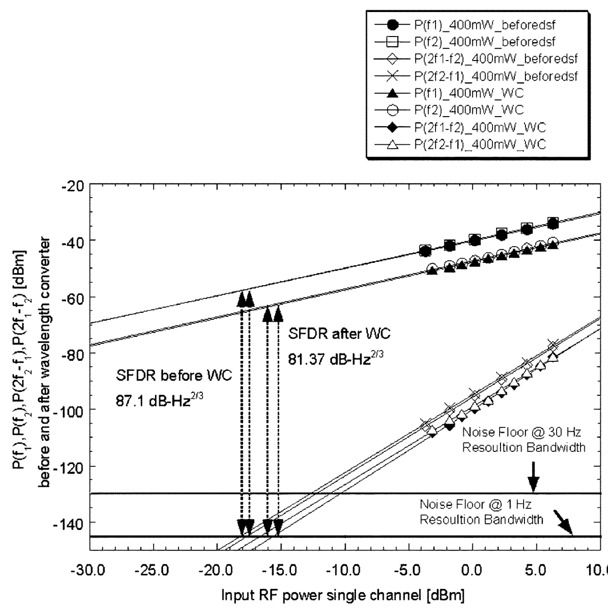

Fig. 3. SFDR measurement before and after DSF for average optical power of 400 mW.

IV. Analog Performance of the Wavelength Converter

The transfer function of the wavelength converter is shown in Figs. 4 and 5 and is obtained by varying the average input optical power of the sampled signal in to the DSF. The power of the CW is kept constant. In order to have good analog performance, the converter must be operated in the linear part of the transfer function. We first measured the SFDR of the back-to-back link defined as the modulator-fiber-photoreceiver without the wave-

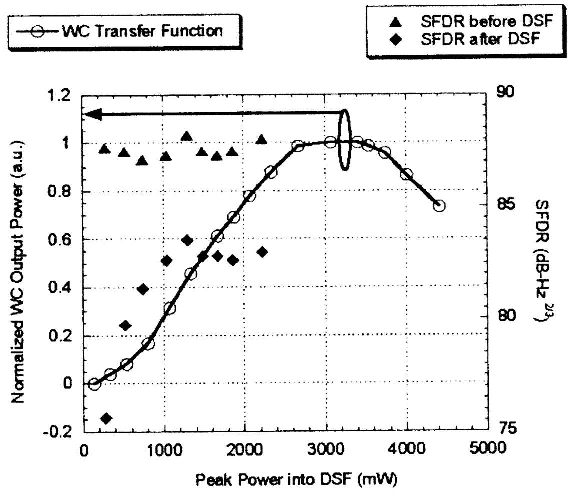

Fig. 4. Measurement of the link SFDR with and without the wavelength converter.

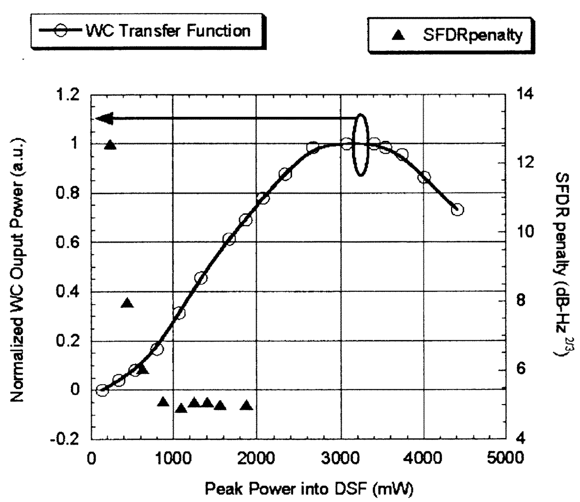

Fig. 5. Calculated SFDR power penalty introduced by the wavelength converter for various points of operation on the transfer function.

length converter. The measured SFDR of the link without the wavelength converter was approximately 86.7 dB $\cdot$ Hz$^{2/3}$. We then measured the SFDR with the wavelength converter inserted in the link at various operating points along the transfer function of the wavelength converter. Fig. 4 is a plot of the SFDR of the link with and without the wavelength converter at various points of operation along the transfer function of the wavelength converter. As observed from Fig. 4, for low-input peak powers into the DSF, the conversion efficiency is very small. This results in a low SFDR value for the link with the wavelength converter. As the input optical signal peak power is increased and we move along the transfer function, we observe that the conversion efficiency increases as the wavelength converter is operated in its linear region. In the linear region of interest, which is between 1–2.4 W of peak pump power, the SFDR of the link is between 82–84 dB $\cdot$ Hz$^{2/3}$. If the optical peak power into the DSF were increased further, we would approach the nonlinear regime of operation of the wavelength converter and would notice a drop in the SFDR value. The transfer function of the wavelength converter was measured with a 10-GHz repetition rate pulse train. These pulses were multiplexed to 40 GHz and used as the sampling source. As the peak power of the 40-GHz pulse train is one fourth of the peak power of the 10-GHz pulse train for the same average power, we could not achieve the peak powers required reach the top of the transfer function and observe the degradation in SFDR. By comparing the measured SFDR with and without the wavelength converter, we are able to establish a measure of linearity penalty introduced by the wavelength converter. Fig. 5 shows the SFDR penalty, defined as the logarithmic difference between SFDR with and without wavelength conversion, versus the input pump power to the DSF. Following the previous discussion, we observe that the SFDR penalty is high for low-input powers into the DSF and then decreases as the wavelength converter is operated in its linear region. From Fig. 5, the SFDR penalty in the linear region of operation of the wavelength converter is about 5 dB $\cdot$ Hz$^{2/3}$. Thus, the fidelity of the wavelength-conversion function is high in the linear region. Linearizing the electrooptic modulator and increasing the efficiency of wavelength conversion can improve the absolute values of the SFDR before and after wavelength conversion.

V. Conclusion

The first measurements of the analog characteristics of ultrafast optical wavelength converters are reported. The SFDR of the wavelength converter was measured between 82–84 dB $\cdot$ Hz$^{2/3}$. The SFDR power penalty is defined by comparing the SFDR of the time-sampled link with and without the wavelength converter in order to access the effect of the wavelength converter on analog system performance. The SFDR penalty in the linear region of operation of the wavelength converter is about 5 dB $\cdot$ Hz$^{2/3}$. The application of analog wavelength converters includes optical A/D conversion as well as switching and beam steering in optical communication links and networks.

Acknowledgment

The authors would like to thank Dr. R. C. Williamson and Dr. J. Hodiak for helpful discussions and comments.

References

[1] L. Rau, S. Rangarajan, H. F. Chou, Y. J. Chiu, D. J. Blumenthal, and J. E. Bowers, "Two-hop all-optical label swapping with variable length 80 Gb/s packets and 10 Gb/s labels using nonlinear fiber wavelength converters, unicast/multicast output and a single EAM for 80 to 10 Gb/s packet demultiplexing," presented at the OFC, Anaheim, CA, Mar. 17–24, 2002, Postdeadline Paper FD2.

[2] A. S. Bhushan, P. V. Kelkar, B. Jalali, and M. Islam, "130-Gsa/s photonic analog-to-digital converter with time stretch preprocessor," *IEEE Photon. Technol. Lett.*, vol. 14, pp. 684–686, May 2002.

[3] P. Toliver, R. J. Runser, D. Kung-Li, I. Glesk, and P. R. Prucnal, "Demonstration of 100 GSa/s analog photonic packet service using analog optical TDM (AOTDM)," in *Proc. LEOS 11th Annu. Meeting*, vol. 1, 1998, pp. 247–248.

[4] W. Ng, R. Stephens, D. Persechini, and K. V. Reddy, "Ultra-low jitter modelocking of Er-fiber laser at 10 GHz and its application in photonic sampling for analog-to-digital conversion," *Inst. Elect. Eng. Electron. Lett.*, vol. 37, no. 2, pp. 113–115, Jan. 2001.

[5] B.-E Olsson, P. Ohlen, L. Rau, and D. J. Blumenthal, "A simple and robust 40-Gb/s wavelength converter using fiber cross-phase modulation and optical filtering," *IEEE Photon. Technol. Lett.*, vol. 12, pp. 846–848, July 2000.