A Novel Class E Analog Fiber Optic Link with RF Power Gain and High DC-RF Conversion Efficiency

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Abstract — **A novel analog fiber optic link is described that incorporates class E switching amplifier techniques in the link architecture to provide RF power gain with high post-detector dc-RF conversion efficiency. The proof-of-concept link was designed to operate at a nominal design frequency of 70 MHz and has an RF gain of 35 dB and a post-detector power amplifier dc-RF conversion efficiency of 78%.**

Index Terms — **optical fiber communication, analog systems.**

I. Introduction

Analog fiber optic links have been developed for various RF, microwave, and millimeter-wave signal distribution applications including antenna remoting and phased arrays. In general, these applications require the distribution of high dynamic range signals for receive applications or the distribution of coherent transmit or local oscillator (LO) signals for transmit applications and frequency conversion. Commercially available analog fiber optic links use either direct modulation of a semiconductor laser or external modulation of a semiconductor or solid-state laser in conjunction with direct detection in a high-speed photodetector [1, 2].

In general, the advantages of analog fiber optic links for signal distribution include small size, low fiber loss, and immunity to EMI. A disadvantage of analog fiber optic links for transmit and LO signal distribution, however, is low photodetector RF output power. Photodetector RF output power is limited by a number of factors including the incident optical power (and hence generated photocurrent) and optical modulation depth. Increasing the optical modulation depth and developing photodectors capable of handling high photocurrents [3] can improve RF output power, but fiber and detector non-linearities [4,5] will limit the improvement that can be achieved via direct detection.

Given the optical power constraints imposed by these nonlinearities, the RF output power delivered to a 50 Ω load for a typical resistively matched analog fiber optic link is on the order of a microwatt (-30 dBm). Thus, a significant amount of post-link RF power amplification is necessary to achieve power levels necessary for direct wireless transmission or for driving mixers. For example, a link with -30dBm output power at the photodetector would require 40dB of post-link power gain to drive a +10dBm level mixer. Thus, it is not uncommon for traditional analog fiber links to exhibit a total dc-RF conversion efficiency as low as a fraction of one percent when both the laser and post-link amplifier dc power consumption are taken into account. For many applications the dc-RF conversion efficiency of the link receiver is the most important efficiency metric since the receiver is located remotely from the transmitter.

In this paper we describe a novel analog fiber optic link that incorporates class E switching amplifier techniques in the link architecture to provide both high RF power gain and dc-RF conversion efficiency [6]. A unique feature of this approach is that while the link input and output signals are analog, the signal that is transmitted over the fiber is digital; a format ideally suited for the fiber channel. The proof-of-concept link described in this paper was designed to operate at a nominal design frequency of 70 MHz (a common radar and communication system intermediate frequency (IF)), and has a measured gain of 35 dB and a post-detector output stage dc-RF conversion efficiency of 79%. To the best of our knowledge, this is the first demonstration of an analog fiber optic link incorporating class E switching amplifier techniques in the link architecture. This work represents a new and novel approach to the distribution of analog transmit and LO signals over fiber.

II. Link Design Approach

A block diagram of the Class E analog fiber optic link is shown in Figure 1. The link consists of a switching waveform generator, a digital optical transmitter, a digital photo-receiver and a class E analog power amplifier. The RF input and output signals are analog. However, the architecture is fundamentally different from traditional analog fiber optic links since a digital pulse modulated signal is transmitted over the fiber. It is instructive to briefly review the electrical class E amplifier prior to describing the link to better understand this approach.

Summary submitted on December 1, 2005.

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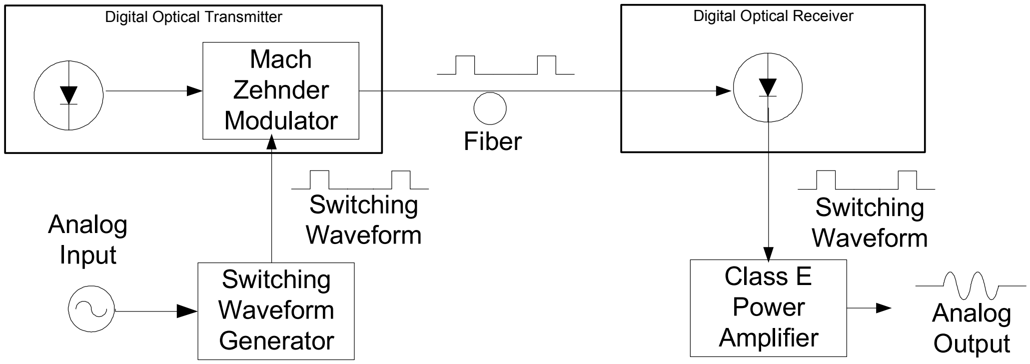


Fig. 1. Functional block diagram the Class E analog fiber optic link

A block diagram of an ideal electrical Class E switching amplifier is shown in Figure 2 [7]. A lossless switch is used to dynamically shunt a capacitor, Cp, and a series RLC tank circuit. The tank circuit ensures that an analog sinusoidal current is produced in the resistive load. Theoretically, this configuration converts DC to RF with 100% efficiency. Output power is maximized when the switching waveform conduction angle is approximately 110 degrees [7] which corresponds to a digital switching waveform with a 30.5% duty cycle. The analog output frequency is equal to the inverse of the switching waveform period.

Most practical electrical class E amplifiers use an FET switch with the analog RF input signal applied directly to the gate to approximate ideal switching conditions. Thus, the electrical class E amplifier has an analog RF input and output and the "digital switching waveform" is generated internally in the FET.

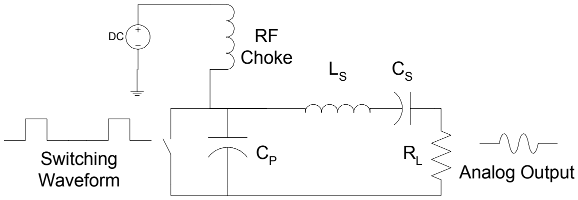


Fig. 2. Functional block diagram an ideal class E switching amplifier

Our approach, shown previously in Figure 1, remotes the digital switching signal from the class E amplifier allowing it to be transmitted over an optical fiber. The switching waveform generator converts the analog RF input signal to the appropriate 30.5% duty cycle digital switching waveform required by the class E power amplifier. The switching waveform then digitally modulates the optical signal which is transmitted over fiber. The digital photoreceiver converts the optical switching signal back to the electrical domain at a signal level which drives the input of a class E switching amplifier.

It should be noted that both high link gain and dc-RF conversion efficiency can be achieved simultaneously using this approach. It is the timing of the switching waveform that is most important, not the amplitude of the waveform (the amplitude simply needs to be scaled properly to interface with the class E amplifier). Dispersion issues associated with digital fiber links are well understood and obviously must be considered in order to maintain good switching waveform fidelity over the fiber link. Further, it should be noted that the 2dB electrical loss for each 1dB of optical loss associated with traditional analog fiber links [1] does not apply to this architecture.

III. PROOF-OF-CONCEPT CLASS E LINK

A proof-of-concept Class E analog fiber optic link was designed for a nominal operating frequency of 70 MHz; a popular intermediate frequency (IF) for radar and communications. The switching waveform generator was implemented using a commercially available comparator which generates a high digital voltage level when the input analog RF signal is greater than a fixed DC threshold voltage and a low digital voltage level when the input analog RF signal is less than the threshold voltage. The comparator DC threshold voltage was selected to ensure that the 30.5% duty cycle switching waveform required for optimum power added efficiency in the class E amplifier was generated.

The digital optical transmitter used a Mach Zehnder Modulator (MZM) to modulate a 1550 nm laser operating at a nominal power of 10 mW. Direct modulation of a semiconductor laser is also possible. A standard p-i-n photodetector was used in the digital receiver. In the future, it is possible that the photodetector could serve as the switching element and be integrated directly into the class E power amplifier. However, for our proof-of-concept link the photodetector output was first amplified by a pulse amplifier to a nominal 3 volt peak-to-peak level. This digital switching waveform was applied to a high-speed GaAs FET that was used as the switch in the class E power amplifier design. The use of the pulse amplifier between the photodetector and the FET switch is not ideal with respect to overall link dc-RF conversion efficiency and it is expected that an improved optical receiver which does not require this pulse amplifier will be discussed in the final paper.

The class E amplifier topology selected for this proof-of-concept link was a classical design [7] realized on a printed circuit. It uses a GaAs FET as the switching element and lumped element components for the switching capacitor and RLC tank circuit. The FET is designed to operate to 6GHz and has an I_{dss} of 140 mA. As is typical with class E designs, the output impedance was low (4 ohms), but easily could be transformed to 50 ohms using well understood techniques [8].

III. Experimental Results

The complete link was constructed and a photograph of the class E amplifier is shown in Figure 3.

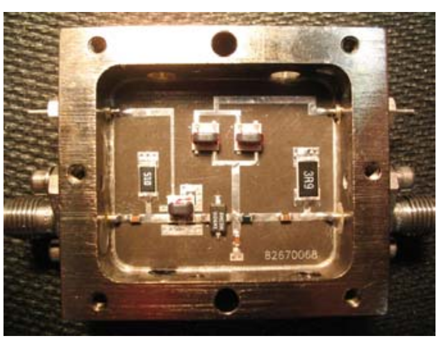
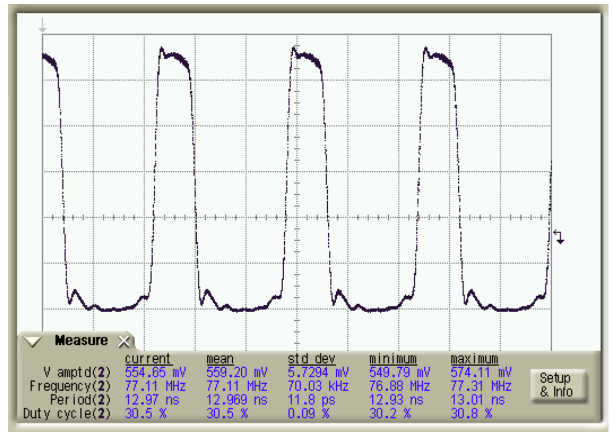
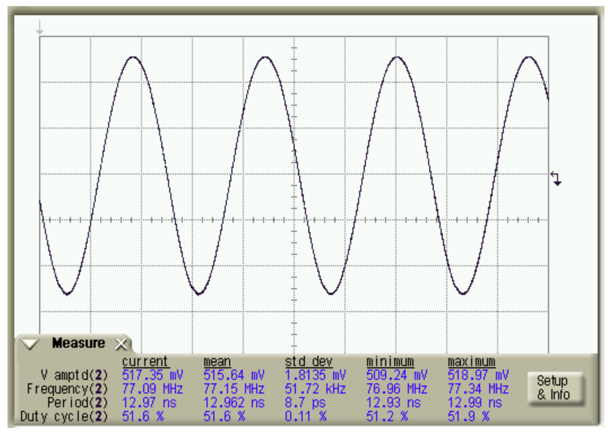


Fig. 3. Photograph of the Class E post-detection amplifier

Figure 4 shows the time domain switching waveform and the output RF signal. A frequency of 77 MHz was used since the amplifier had the best experimental performance at this frequency. The deviation from the nominal design frequency of 70 MHz is being investigated and likely was due to a combination of component value tolerances and parasitics in the class E amplifier.



(a)



(b)

Fig. 4. (a) Measured digital switching waveform at the output of the photoreceiver; (b) measured waveform at the output of the Class E analog fiber optic link (i.e. output of class E amplifier). Both waveformas are taken at 77 MHz.

Figure 5 shows the spectrum of the RF output signal.

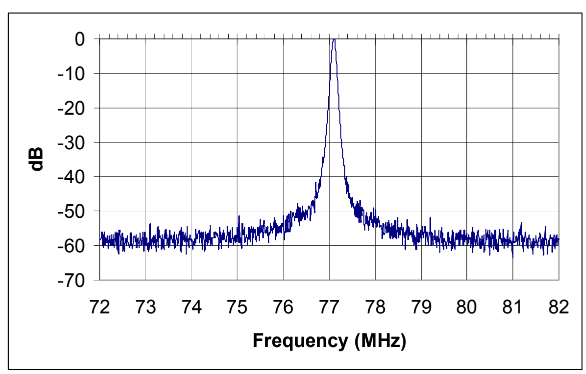


Fig. 5. Class E Fiber Optic Link Output spectrum at 77 MHz.

The class E amplifier dc power consumption, RF output power, and power added efficiency were simulated and measured between 60 and 80 MHz and are shown in Figure 6. As previously noted, the output power was delivered to a 4 Ω load. The power added efficiency, η , was computed as shown below where P_L is the RF power delivered to the load and P_{dc} is the dc power.

$$\eta = \frac{P_L}{P_{dc}} \times 100$$

The simulated results are in good agreement with the measured results. For example, in Figure 6 the measured RF output power at 77 MHz is only a 1.3 dB discrepancy.

IV. Conclusions

A novel analog fiber optic link has been described which uses class E amplifier concepts in the link architecture. While the link input and output are analog, a digital signal is transmitted over the fiber optic link. The frequency of the digital waveform corresponds to the desired analog frequency while the duty cycle of the digital waveform is set to approximately 30% to achieve high post-detector dc-RF conversion efficiency. A proof-of-concept link was designed and experimental results are presented which include 35 dB of RF gain and 79% dc-RF conversion efficiency in the class E amplifier. Several improvements are currently being pursued and we expect to report on increased output power and gain (with similar efficiency) and an improved photoreceiver that is designed to interface directly to the class E amplifier. It should be noted that electrical class E amplifier technology has been demonstrated at 10 GHz [9] so extensions of this link approach to higher frequencies are possible.

Acknowledgment

This work was partially supported by the US Government.

References

[1] C. H. Cox, *Analog Optical Links; Theory and Practice.* New York: Cambridge University Press, 2004.

[2] C. H. Cox, E. A. Ackerman, "RF-Fiber-Optic Link Performance," *IEEE Microwave Magazine,* vol. 2, pp. 50-58, Dec. 2001.

[3] D. A. Tulchinsky, *et. al.*, "High-Saturation Current Wide-Bandwidth Photodetectors," *IEEE Journal of Selected Topics in Quantum Electronics,* vol. 10, no. 4, pp. 702-708, July/August 2004.

[4] R. D. Esman, K. J. Williams, "Measurement of Harmonic Distortion in Microwave Photodetectors," *IEEE Photonics Technology Letters,* vol. 2, no. 7, pp. 502-504, July 1990.

[5] G. P. Agrawal, *Fiber-Optic Communication Systems, 3rd Ed, Ch.6.* New York: John Wiley and Sons, Inc., 2004.

[6] Patent pending

[7] S. C. Cripps, *RF Power Amplifiers for Wireless Communications, Ch. 6.* Boston: Artech House, 1999.

[8] A. Grebennikov, "Load Network Design Techniques for Class E RF and Microwave Amplifiers," *High Frequency Electronics,* pp. 18-32, July 2004.

[9] N. Wang, et. al., "60% efficient 10-GHz power Amplifier with Dynamic Drain Bias Control, IEEE Transactions on Microwave Theory and Techniques, vol. 52, no. 3, pp. 1077-1081, March 2004.

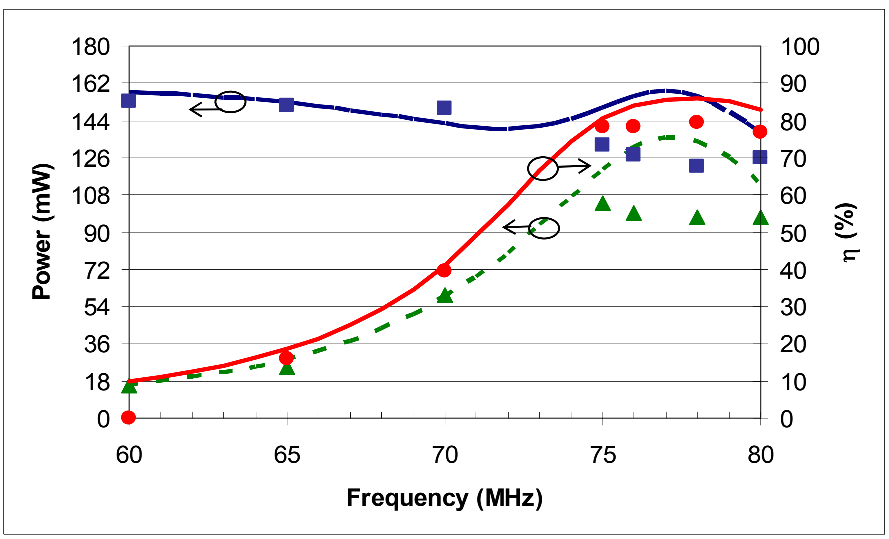


Figure 6. (— —) simulated DC power consumption; (■) Experimental DC power consumption; (- - -) simulated RF output power; (▲) experimental RF output power; (——) simulated power added efficiency; (●) experimental power added efficiency.