Letter

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Novel Equalization Technique for Optical Sources with Direct Modulation

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In this letter, a novel equalization method for directly modulated optical sources is introduced. Conventional source equalization methods balance the low and high-frequency responses of the source by cutting down the low-frequency components in any drive signal. Typically, this ensures a flat frequency and linear signal response up to some predetermined upper-frequency limit. It is conventionally done under a fixed linear dynamic range. However, in this paper, it is found that source's dynamic range varies by frequency. We describe a novel method that determines the limit of signal linearity at each frequency and uses this to create the enhanced equalizer response. This leads to an improved source bandwidth and in practice allows greater transmitted signal energy. Experimental results for a resonant cavity LED transmitter show date-rate improvement of ~40% and to the best of our knowledge, a record date-rate of 8.76 Gb/s, with bit-error-rate less than 3.8x10^{-3}.

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Intensity modulated optical links are widely used for fields such as LiFi and data transmission using optical fibers. LEDs typically have high power available but low modulation bandwidth so complex signal modulation schemes such as Orthogonal Frequency Division Multiplexing (OFDM) are used to maximize the capacity available. For the intensity modulation, a direct modulation method is frequently used. Using the direct modulation, the optical output of the source varies according to the applied electrical input signal.

A popular way to further improve the bandwidth (BW) of the source in the direct modulation is to use an equalizer [1-3]. The equalizer 'flattens' the channel response, and so that the desired waveform is transmitted un-distorted until the predetermined equalization BW. A linear filter is typically used to do this, and this can be placed at the transmitter (pre-equalization), and/ or at the receiver (post-equalization). Pre-equalization typically suffers from dynamic range limitations in the optical source, limiting the modulating electrical energy that can be transmitted through the optical source [1]. Post-equalization compensates the distortion in the received signal, but the noise level is enhanced while compensating the low-frequency components, due to the noise accumulated through the end of the system.

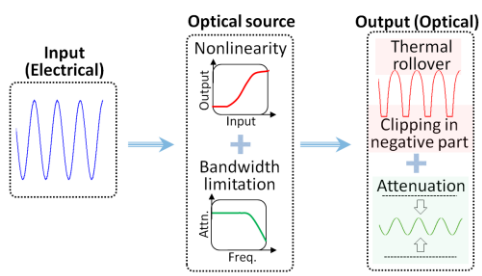

Fig.1. Schematic diagram showing the output signal distortion due to the non-linearity and bandwidth limitation of optical source

In this letter, a novel equalization method that mitigates the drawbacks of the conventional equalizer is introduced. We first analyze the frequency dependent nonlinearity of the optical source by a series of experiments. Then, taking advantage of the characteristics of this frequency dependent nonlinearity, a method to apply more signal energy to the source is presented. This method preserves linearity and increases the date-rate. A demonstration with a record date-rate using this new equalizer is also presented.

The output signal from the optical source can be distorted and/or attenuated mainly by nonlinear transfer function and inherent BW of the source, as shown in Fig. 1. The nonlinearity becomes problematic mainly when a large signal swing is applied to the source, exceeding its linear dynamic range, conventionally set by the DC response of the source. This makes the negative

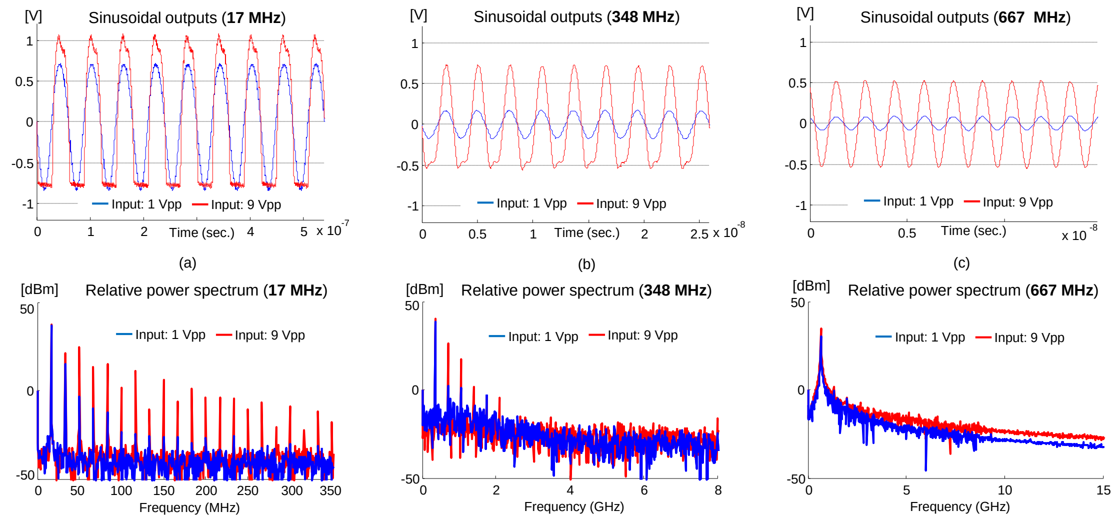

Fig. 2. Time (up) and frequency (down) domain analysis of sinusoidal outputs from RC-LED with input voltage swing of 1 Vpp and 9 Vpp, at (a) 17 MHz, (b) 348 MHz, and (c) 667 MHz

intensity part clipped and high-intensity part distorted by thermal rollover [4]. The inherent BW of the source limits the modulation speed by attenuating high-frequency components beyond the BW of the source.

Since the output signal can vary by applied frequency and strength of the applied input signal, various cases are tested in this letter. Figure 2 shows time and frequency domain analysis of sinusoidal outputs from a resonant-cavity LED (RC-LED, RC650, 100 MHz BW) with input voltage swing of 1 Vpp and 9 Vpp, at (a) 17 MHz, (b) 348 MHz, and (c) 667 MHz. The signal is generated from an arbitrary waveform generator (AWG, M8190A, 5 GHz BW) followed by an amplifier (ZFL2500VH, 2.5GHz BW). To investigate the impact of large signal swing beyond its linear dynamic range, 1V and 9V are chosen for a normal and over-driving case, respectively. 9V is high enough to generate sufficient harmonics but still showing reliable results for the device under test (RC650). The tested frequency sets are chosen since they are good representatives of low, medium and high frequency showing the effect of nonlinearity when band-limited. The output signal is detected by a free-space photo receiver (Femto, 1.4GHz BW) followed by an oscilloscope (MSO9254A, 2.5GHz BW). At 17 MHz, when 9 Vpp is applied to the RC-LED, there are clear hard clipping in the lower part and single distortion in the upper part observed in the time domain signal. As increasing the frequency, however, the nonlinear distortion is getting smaller. At 348 MHz, in the frequency domain, the high-frequency harmonics caused by the large input swing of 9Vpp are suppressed. This can be explained as the harmonics constructing the nonlinear distortion being suppressed as the frequency exceeds the BW of the RC-LED. At 667MHz, an almost linear response is observed, with the output increasing proportionally to

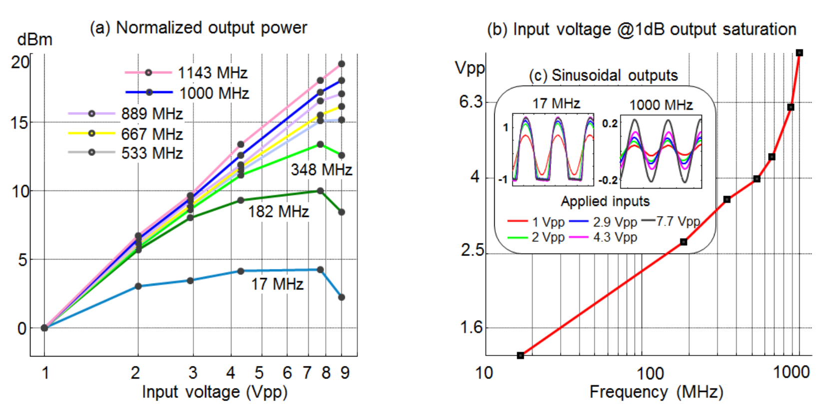

Fig. 3. (a) Normalized electrical output power by increasing the sinusoidal input voltage swing at various frequencies, (b) input voltage leading to 1 dB output power reduction with waveforms (inset) showing the improved linear dynamic range from 17MHz to 1000 MHz

the input. This means that the linear modulation transfer function of the source differs by the modulation frequency.

With these findings in mind, a novel hard-clipping equalizer (HCE) is introduced. The principle behind this method is to maximally boost the high-frequency components to compensate attenuation by the source whilst preserving the linearity. For this, the maximum input signal levels resulting in linear response at different frequencies should be first found. Figure 3(a) shows the normalized electrical output power by increasing the sinusoidal input voltage swing at various frequencies. The higher the input frequency is, the more linear response is observed. Figure 3(b) shows the input voltage swing leading to 1 dB output power saturation. To define the linear input dynamic range, a popular metric of 1dB electrical power saturation (~10% optical power reduction) is used, although different metrics can also be applied. In the output sinusoidal waveforms at 17MHz and 1000MHz, as shown in the inset, the improved linearity can be confirmed. The linear input dynamic range differs by frequency although it has been conventionally thought to be a fixed value.

Equation (1) shows a frequency response of conventional equalizer (H_{EQ}), where H_{source} is source frequency response, BW_{source} is BW of the source, and BW_{EQ} is equalization bandwidth. This equalizer flattens the source response up to BW_{EQ}, by applying the inverse of H_{source}.

$$H_{EQ}(f) = \begin{cases} \dfrac{H_{source}(BW_{EQ})}{H_{source}(BW_{source})} H_{source}^{-1}(f) & , f \le BW_{EQ} \\ 1 & , f > BW_{EQ} \end{cases} \quad (1)$$

$$\cong \left(\frac{BW_{source}}{BW_{EQ}} \right)^m \frac{1 + j\left(f / BW_{source}\right)^m}{1 + j\left(f / BW_{EQ}\right)^m} \quad (2)$$

Equation (2) shows the equalizer frequency response simplified by a high-pass filter model. This approximation is valid as typical LEDs and LDs show responses decaying exponentially with a frequency beyond their BWs. The exponent (m) represents the slope of the source frequency response with -20·m dB per decade. It can be seen from Eq (2) that when the frequency exceeds BW_{EQ}, H_{EQ} becomes 1, making the source equalized until BW_{EQ}. However, for this conventional equalizer, DC gain ($H_{EQ}(0)$) should be lowered by $(BW_{source}/BW_{EQ})^m$. Therefore, a significant power reduction should be accompanied as BW_{EQ} exceeds BW_{source}.

HCE allows a unity DC gain, solving the issue fundamentally, with the use of linear input dynamic range defined in the frequency domain. A way to implement HCE is conceptually shown in Fig. 4(a) diagram. High-frequency components of the input signal are increased through HCE, built as a linear filter plus an amplifier creating the pre-designed coefficients in the frequency domain. Then, the conditioned signal is applied to the optical source via BiasT with a DC addition.

Figure 4(b) shows schematically how the equalizer operates. The channel response (in green) is compensated by the conventional equalizer (dotted blue) so that the maximum amplitude is at the edge of the nonlinear region (as determined at low frequency). There is, however, an 'unused' part of the linear region (marked in red) that this equalizer exploits. This can be achieved by applying HCE response which flattens the response until BW_{EQ} using signal amplitude that is just in the linear region at

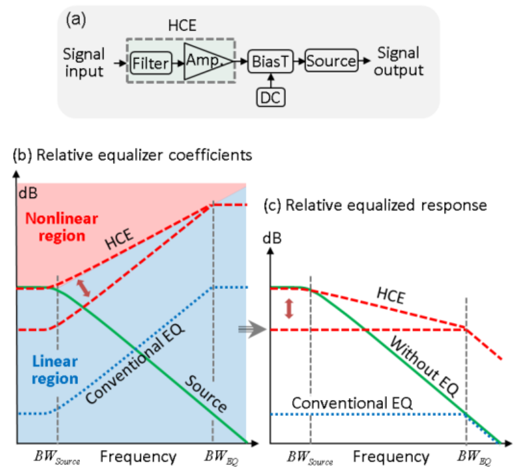

Fig. 4. (a) Schematic diagram of HCE applied to optical source, (b) relative equalizer coefficients, and (c) relative equalized output response

the highest frequency. Comparing this with the conventional equalizer it can be seen from Fig. 4(c) that additional energy can be transmitted. Alternatively, a response that ensures the maximum use of the linear region at all frequencies can be used. This results in a sloping channel response, yet maximizes the applied energy whilst maintaining a linear output response. For both cases, considerably higher gain can be achieved as the BW_{EQ} exceeds BW_{source}. The conventional post equalizer can still be applied along with HCE when the amplification for the HCE is practically not enough or when compensating the residual aliasing is needed.

In order to test this novel HCE equalization, an optical wireless communication system is built as shown in Fig. 5(a). First, a PC creates a communication signal converted to an analogue signal through an AWG. The signal is sent to an amplifier, followed by a DC source and a bias-T. In this case, the HCE coefficient is generated by the AWG and the amplifier. The signal scaled by the HCE coefficients is applied to an RC-LED. The HCE coefficients are prepared according to the newly defined linear dynamic range by frequency as shown in Fig. 3 (b).

The light emitted from the source is collimated, transmitted, focused, and then detected by a high-speed photo receiver. The signal is captured by an oscilloscope and fed back to the PC. The applied modulation scheme is DC biased optical orthogonal frequency division multiplexing (DCO-OFDM). DCO-OFDM is chosen for its high spectral efficiency which is desirable for the band-limited scenario being investigated in this work. Detailed block diagram and characteristics of DCO-OFDM in comparison with other optical-OFDM schemes can be found in [5].

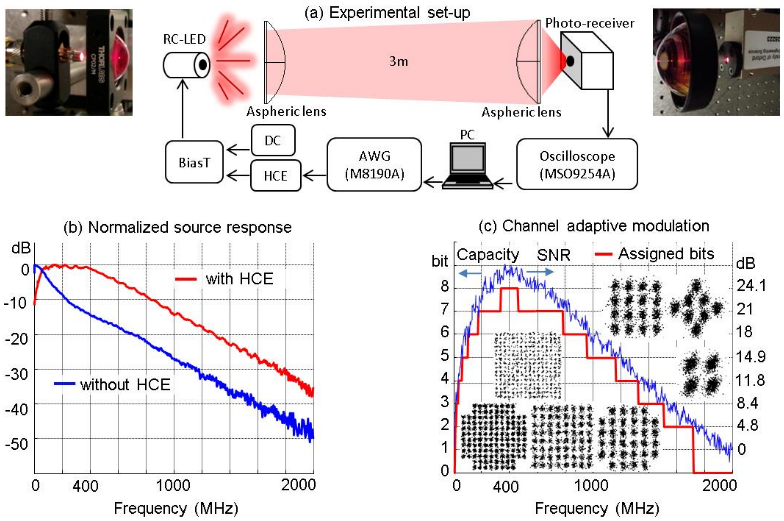

Fig. 5. (a) Optical wireless communication set-up to demonstrate HCE, (b) Normalized source frequency response with and without HCE, and (c) allocated number of bits from rate adaptive DCO-OFDM scheme resulting in 8.76 Gb/s (BER<3.8×10^{-3}), with channel capacity calculated from measured SNR and received constellations

To optimize DCO-OFDM performance, signal conditioning is required with respect to the signal-to-noise ratio (SNR) and the channel gain. Using the methods in [6], the parameters for DCO-OFDM are optimized for this demonstration. Time domain signal clipping outside ±3.8σ is applied to restrict high peaks of the DCO-OFDM signal, where σ is a time domain signal standard deviation. Fast-Fourier-Transform size and cyclic-prefix size of 1024, 10 are respectively used. To improve the performance further, a rate adaptive bit-loading is applied [7]. Figure 5(b) and (c) show the normalized source frequency response with and without HCE, and the allocated number of bits from the rate adaptive DCO-OFDM scheme resulting in 8.76 Gb/s.

The channel capacity calculated from the measured SNR and the received quadrature amplitude modulation (QAM) symbol constellations are also shown. The improved frequency response by HCE allows large bits to be carried on the DCO-OFDM signal, which is closely upper-bounded by the calculated capacity. In the demonstration, bit-error-rate (BER) of < 3.8×10^{-3} is used as a reliable communication link is guaranteed by this BER with a standard forward error correction (FEC) code with 7% overhead [8]. Subtracting the overhead, the data-rate becomes 8.1 Gb/s. The ratio of the data-rate over the available source bandwidth is often used as a metric to compare the efficiency of communication schemes. In this demonstration, a ratio of 81 is achieved by combining HCE and rate-adaptive DCO OFDM. This is a considerable improvement, compared to some representative work with a high ratio, such as 50 ($=\frac{3\text{Gb/s}}{60\text{MHz}}$) in [9].

In this letter, the nonlinear behavior of the optical source in BW limited cases was studied. Since the linear input dynamic range can be increased at high frequencies, the novel equalizer (HCE) maximizing the use of the linear range was introduced.

A high-speed RC-LED based optical wireless communication link was demonstrated with the novel equalizer. A date-rate improvement of ~40% was obtained compared to the case without HCE. Also, the achieved data-rate is the fastest result reported in a single LED based optical wireless link, to the best of the author's knowledge. Future work includes an accurate modelling of frequency dependent nonlinear behavior of both optical sources and detectors, as well as finding new applications benefitting future optical systems.

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