Experimental Demonstration of Bipolar Codes for Direct Detection Multi-user Optical Communication¹

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Abstract — We report the first experimental demonstration of a broadband spectral encoding and decoding technique using bipolar codes for optical code-division multiple access. The code-word correlations are verified and rejection of multiple-access interference is demonstrated.

I. INTRODUCTION

The application of code-division multiple access techniques in the optical domain has not been very successful, primarily due to the unipolar nature of the direct detection optical channel. Recently we proposed an all-optical encoding and detection method that is equivalent to the use of bipolar spreading codes in the radio domain [1]. The technique uses the broad bandwidth of the optical channel to create an effective bipolar channel using longer unipolar codes. In the spectral encoding realization, a portion of the spectrum from an erbium-doped superfluorescent fiber source (SFS) [2] is encoded using a grating and amplitude mask.

II. EXPERIMENTS

Fig. 1 illustrates the geometry for each encoder module in the system. A planar holographic grating of 1200 grooves/mm disperses the SFS beam, and the first-order spectrum is collected and collimated by the concave-spherical mirror 1. On the amplitude mask, the spectrum is formed to a 30 μm high horizontal stripe, where 1 nm of optical bandwidth corresponds to 1 mm of horizontal distance. The mask pattern is the concatenation of the unipolar code U and its binary complement $\bar{U}$, where U is obtained from a length- N bipolar code, by replacing each -1 with 0. Portions of the spectrum reflected off the amplitude mask are collected on mirror 1 and focused back to the grating surface. The recombined beam exits the encoder module representing the "0" symbol. The remaining portion of the spectrum, the spectral complement of the reflection, is transmitted by the amplitude mask and returned to the grating by mirror 2, forming the beam representing the "1" symbol. ON/OFF modulation of the "0" and "1" beams of the encoder forms the binary information symbol.

The geometry for each decoder module is the same as the encoder, with the transmission channel replacing the SFS beam. For the decoder, the "0" and "1" output beams are coupled to a balanced photodetector

pair, where the detector current represents the true bipolar correlation of the codes at the encoder and decoder. Fig. 1 also shows the mask patterns of one length-16 and two length-32 codes (from bipolar Walsh codes of lengths 8 and 16), denoted A, B and C, respectively. The chip widths vary to compensate for the non-uniform source spectrum, so that the per-chip power is uniform as required by the coding. Mask patterns are created on glass substrates by photo-etching an evaporated aluminum coating.

Fig. 1: Geometry for the grating based encoder/decoder modules, and the mask codes A, B, and C.

Prior to measuring the correlations and demonstrating the rejection of multiple-access interference (MAI), we made a measure of the total dispersion and resolution for the encoder-decoder system. A special mask, comprised of three 100 μm (0.1 nm bandwidth) chips spaced 2.5 mm (2.5 nm spectral separation) was fabricated for the encoder and decoder. A mask convolution was performed, whereby the mask of the decoder was moved horizontally with respect to the incident beam, while the total transmitted power through the decoder mask was recorded. Shown in Fig. 2 are three measured peaks corresponding to the alignment of all three chips, two chips, and just one chip, as viewed from right to left. Plotted with a dashed line is the theoretical convolution curve for the masks. From the shifted location of the smaller measured peaks, a distortion of 100 μm over a 5 mm field in the decoder mask plane is apparent. In addition, it is also clear from the plot that the width of the measured peaks is larger than theory predicts. Ideally, the convolution of two 100 μm chips should result in a triangular spatial distribution of power with a base of 200 μm width.

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If the linear slopes of the measured peaks are extended to the horizontal axis, the base of the largest distribution is at least $500\text{ }\mu\text{m}$. Applying the Rayleigh criterion, the minimum chip spacing for this system, or equivalently the minimum chip size, is estimated to be $250\text{ }\mu\text{m}$. The amplitude of the measured peaks is not proportioned as theory would predict, an effect that can be attributed to the non-uniformity of the source spectrum. Since only $\sim 10\%$ of the grating surface is currently illuminated, expansion of the incident beam should result in improved resolution for future experiments.

Fig. 2: The intensity pattern obtained from convolving the $100\text{ }\mu\text{m}$ chip mask to test the total resolution and dispersion of the system.

The correlation measurements were performed with a single user system, comprised of one encoder module matched to one decoder module. The results are shown in Fig. 3. Separate graphs (a,b,c) are presented for each code

Fig. 3: Correlations of the codes seen on the oscilloscope. Plot (a) shows the correlations for user A, plot (b) for user B, and plot (c) for user C.

positioned at the decoder, plotting the balanced receiver voltage as a function of the code sent by the encoder. The DC voltage levels shown are the actual waveforms stored by the oscilloscope during each correlation. For each

graph, when the encoder is matched to the decoder, a large positive or equally large negative auto-correlation is recorded. Conversely, when the encoder sends a code that does not match the decoder, a small cross-correlation value is recorded, which in all cases is measured to be less than 8% of the auto-correlations. The good contrast between the auto- and cross-correlation values shows that a binary information symbol can be recovered by an appropriate threshold operation.

The rejection of MAI was demonstrated with a two user system, comprised of two encoders coupled to one decoder. Shown in Fig. 4 are the results of matching the desired user's code to B or C while varying the interference user's code. The plots show the amount of interference detected by the desired user, obtained by subtracting the desired user's auto-correlation from the signal measured with two users. As expected, the decoder cannot make a discrimination when the interference user is matched to the desired user's code, as evidenced by the large values for the B codes of plot (a) and the C codes of plot (b). For the other codes, the interference level is equal to or less than 10% of the desired signal, demonstrating the capability of the decoder to reject MAI.

Fig. 4: Waveforms obtained from subtracting the autocorrelation value from the two-user waveform stored by the oscilloscope. Plot (a) is the measured interference for user B, plot (b) is for user C.

III. CONCLUSION

We have presented experimental results that demonstrate the use of bipolar codes for spectral encoding and decoding in optical code-division multiple-access. The auto- and cross-correlation measurements have shown that a binary information symbol can be recovered using an appropriate threshold operation. Multiple-access interference has been shown to be rejected in a multi-user situation. Technical improvements in the spectral encoding and decoding process are likely to lead to improved system performance and enhanced practicality for use in optical CDMA.

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