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**A Cleary<sup>1</sup>, I Veres<sup>2</sup>, G Thursby<sup>1</sup>, C McKee<sup>1</sup>, I Armstrong<sup>1</sup>, S G Pierce<sup>2</sup>, B Culshaw<sup>1</sup>**

<sup>1</sup>Centre for Microsystems and Photonics, Department of Electronic and Electrical Engineering, University of Strathclyde, Glasgow, G1 1XW

<sup>2</sup>Centre for Ultrasonic Engineering, Department of Electronic and Electrical Engineering, University of Strathclyde, Glasgow, G1 1XW

Email: alison.cleary@eee.strath.ac.uk

**Abstract.** The use of low power modulated laser diode systems has previously been established as a suitable method for non-destructive laser generation of ultrasound. Using a quasi-continuous optical excitation amplified by an erbium-doped fibre amplifier (EDFA) allows flexible generation of ultrasonic waves, offering control of further parameters such as the frequency content or signal shape. In addition, pseudo-random binary sequences (PRBS) can be used to improve the detected impulse response. Here we compare two sequences, the m-sequence and the Golay code, and discuss the advantages and practical limits of their application with laser diode based optical excitation of ultrasound.

## **Introduction**

The use of low power continuous wave laser diodes for generating ultrasound is an established technique [1,2]. In contrast to the high peak power, short pulse lasers more commonly used in laser generated ultrasound [3,4], laser diodes offer the option of distributing the excitation energy over a longer pulse or a sinusoid to help avoid ablation damage to the sample.

The excited ultrasonic waves have very low amplitude and for the case of sinusoidal excitation, lock-in detection is required; the excitation frequency is stepped through the range of interest. For pulsed or toneburst excitation however, lock-in detection is unsuitable and the data is typically averaged and captured on an oscilloscope. In this case, signal processing or coded excitation for noise reduction becomes attractive.

One such method of noise reduction is to use PRBS coded pulses as excitation, as demonstrated by Pierce [5,6] who used 850 nm optical excitation and interferometric detection. Madaras and Anastasi have also demonstrated a similar method, using a contact transducer for detection [7]. Here, we show how coded excitation can be used in conjunction with a laser diode at 1550 nm, where an EDFA can be used for optical amplification.

## **PRBS coding**

The two types of sequence described here are the m-sequence and the Golay code [8,9]; they use a pseudo-random train of pulses rather than a single repeated pulse. M-sequences consist of a pseudo-random train of  $2^N-1$  pulses of magnitude 1 or -1, where N is an integer. The autocorrelation function is an almost perfect delta function with magnitude  $2^N-1$ . However, as optical pulses cannot be negative, the pulse train must be modified to be a set of 1's and zeroes [10,11]. This modification influences the zero frequency component and reduces the amplitude of the autocorrelation function by a factor of four. Golay codes are more complex, but the autocorrelation function is perfect. They are a set of two complementary codes with magnitudes of 1 or -1. The two codes are then decomposed into two further series that consist of 1's and zeroes, which are suitable for optical excitation. Each code is sent separately to the sample excitation, and then the four measured responses are combined together through cross-correlation [9,13]. Its autocorrelation function has magnitude  $2 \times (2^N)$ .

By cross-correlating the ultrasonic signal with the original pulse stream that was sent to the sample, the unique properties of the autocorrelation functions mean that the final recovered signal is the impulse response with increased amplitude. Therefore, the PRBS coding acts as a type of smart averaging where it is not necessary to wait for each individual pulse response to decay before inputting the next, and so the acquisition time required for averaging is considerably reduced.

### Experimental setup

The optical excitation consisted of a distributed feedback (DFB) laser diode which was modulated through a bias tee with an arbitrary function generator, and amplified using an EDFA. The output power from the EDFA was 1 W, and the power incident on the sample was approximately 0.8 W. The output from the EDFA was focussed onto the sample surface using a single element lens, and the smallest  $1/e^2$  spot size was measured to be 30  $\mu\text{m}$ . Figure 1 shows the experimental setup.

[[pic]  
 |Figure 1. Experimental setup, where AFG is arbitrary function  
 |generator, LDC is laser diode controller, BT is bias tee, LD is  
 |laser diode and EDFA is erbium doped fibre amplifier. |

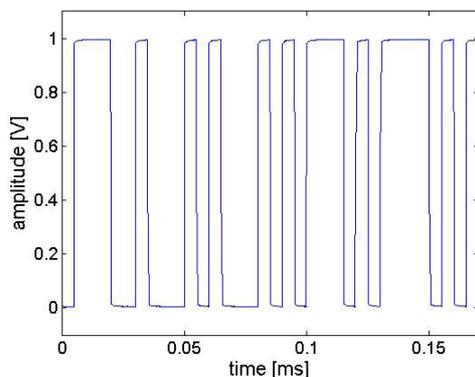
Detection was with a Polytec OFV303 vibrometer, using a displacement decoder with 20 MHz maximum bandwidth. The output from the vibrometer was sent directly to an Agilent Infiniium oscilloscope. The sample under test was a 12.5  $\mu\text{m}$  thick brass plate which was mounted vertically to enable the detection beam to be placed on the opposite side of the plate from the excitation. The source and detection spots were aligned to be within approximately 1 mm of each other, but some drift was observed during the course of the experiments.

M-sequence excitation was provided by sequences of length 2047 ( $2^{11}-1$ ) and 8191 ( $2^{13}-1$ ) bits, and Golay codes of length 2048 bits were used. Single pulse excitation was also used for the purpose of comparing responses from the coded sequences. All measurements were averaged on the oscilloscope 4096 times.

### Results

#### M-sequences

A set of measurements under identical excitation and detection conditions were recorded for an individual pulse at 200 kHz and m-sequences of length 2047 and 8191 bits, again at 200 kHz. Control of the frequency content of the pulses is achieved by varying the width of the individual pulses within the sequence. This means that every element (1 or 0) in the m-sequence has a width of (1/200 kHz) or 5  $\mu\text{s}$ . Figure 2 shows a segment of the 2047 bit input m-sequence as recorded on the oscilloscope, and figure 3 shows the response from two different length m-sequences after cross-correlation.



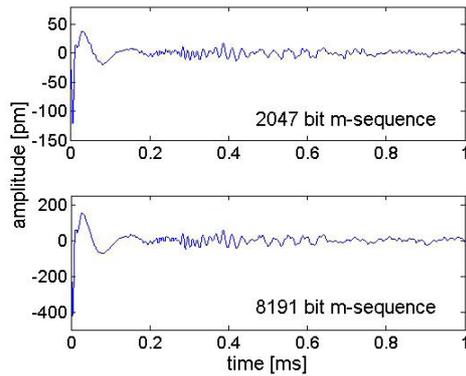


Figure 2. Segment of the 2047 bit m-sequence used as input to the DFB laser diode.

Figure 3. Response from two different length m-sequence measurements

The increase in maximum amplitude between the two sequences is approximately fourfold, corresponding to the increase in the number of bits in the m-sequence.

The frequency response of the 8191 bit m-sequence measurement at 200 kHz is shown in Figure 4, showing that the first null occurs at 200 kHz, and that most of the energy is concentrated in the frequencies up to 200 kHz.

#### SNR enhancement

If the noise level can be significantly reduced by using coded excitation, there is a chance to detect the small displacement signals associated with low power laser generated ultrasound. The expected SNR enhancement with respect to a single pulse measurement for a perfect m-sequence is  $\sqrt{2^N-1}$  and for Golay codes  $\sqrt{2^N}$  [12,13]. This would correspond to enhancements of 45 and 90 for m-sequences of 2047 ( $2^{11}-1$ ) and 8191 ( $2^{13}-1$ ) bits respectively. As we have used imperfect m-sequences with pulses of 1 and zero, the expected SNR is reduced by a factor of four. An increase by a factor of 11 for the 2047 bit and 23 for the 8191 bit m-sequence with respect to the single pulse measurement is then anticipated. The maximum SNR was measured by taking the maximum signal amplitude and dividing by the average noise value in each case. In practice, we found the maximum SNR was improved by factors of 20 and 36 for the 2047 and 8191 bit sequences.

#### Golay codes

The SNR obtained with Golay code excitation should be better than that seen with the m-sequences, as a perfect Golay code has a larger autocorrelation function. Figure 5 shows an example of a 2048 bit Golay code measurement at 200 kHz and that of a single 200 kHz pulse response. The SNR improvement between these measurements was expected to be  $\sqrt{2^N}$  which is 45, but was measured as 102. The greater than expected improvement seen is thought to be due to errors in the noise estimation.

Golay codes are also more suitable than m-sequences for the case where the pulses are used as a trigger for a more complex waveform such as a toneburst, as they consist only of pulses of magnitude  $\pm 1$ , and therefore the autocorrelation function in practice allows a more complete reconstruction of the original signal. This is beyond the scope of this paper, but will be described in a future communication.

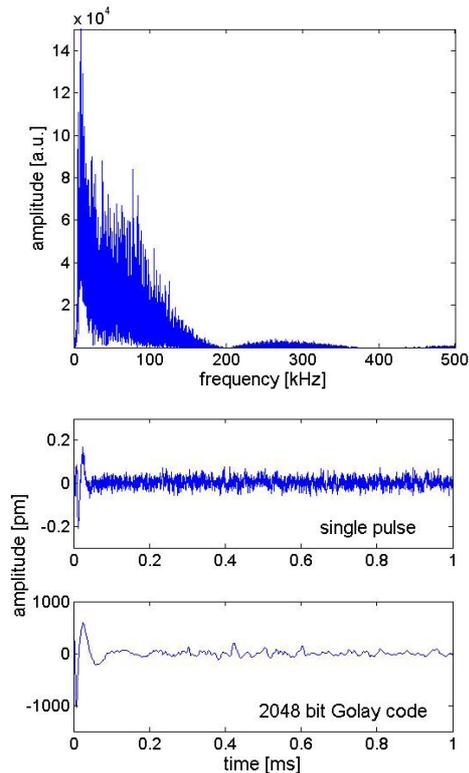


Figure 4. Fourier transform of an 8191 bit m-sequence.

Figure 5. Response to 200 kHz pulse, and a 2048 bit Golay code excitation.

## Conclusions

We have shown experimentally how both m-sequences and Golay codes can be used in the laser generation of ultrasound. M-sequences codes have to be modified from their original form for optical excitation, thus reducing the SNR enhancement in comparison to an equivalent length Golay code. The SNR in the case of both m-sequences and Golay codes was improved by increasing the length of the coded sequence and corresponded reasonably well to theoretical expectations.

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scope

AFG

sample

LD

LDC

vibrometer

EDFA

BT