DATA TRANSFER BY ELASTIC WAVES IN DISSIPATIVE IRREGULAR CAVITIES USING TIME REVERSED CODING

R. Sprik
van der Waals-Zeeman Instituut, Universiteit van Amsterdam, The Netherlands
sprik@science.uva.nl

Abstract

In highly scattering environments waves still obey under very general conditions time reversal and reciprocity symmetry. These universal symmetry properties can be exploited to code signals for efficient data transfer in scattering media. The concept of time reversed coding and the use in data transfer is demonstrated in a 2D cavity consisting of a thin silicon wafer. Arbitrary modulated compression waves at ≤ 1 MHz are generated and detected by small ultrasonic transducers. The strong mode mixing in the wafer between shear and compression waves is not destroying the time reversal and reciprocity symmetry in the system. The reverberation time of the cavity is in the millisecond range. By using time reversal coding of a pulsed signal, increased data transfer rates 200 fold in excess of the inverse of the reverberation time are achieved.

Introduction

Strong scattering of waves between transmitter and receiver need not be detrimental in obtaining high communication rates. By using multiple receivers and transmitters in strongly scattering environments a considerable rate enhancements can be achieved by appropriate (de)coding of the signal [1], [2]. Essential in achieving the enhancement is that the multiple scattered signals form independent and de-correlated communication channels. According to information theory the maximum attainable transfer rate scales with the number of available independent channels [3]. In a strongly scattering medium were the scattering mean-free-path of the waves is much shorter than the transmitter to receiver distance, antennas that are further apart than the wavelength act as independent channels. Recent results in wireless radio communication at 2GHz demonstrate enhancements using multiple antenna arrays and a special encoding and decoding algorithm [4]. The transfer matrix describing the coupling between all possible transmitter and receiver combination contains the necessary information for the coding. The wave propagation in the scattering medium determines these coupling strengths including effects of scattering, diffraction absorption etc. Apart from spatial de-correlation of channels also diversification in polarization, direction and time can be exploited to increase the number of independent channels [5].

In highly scattering environment waves still obey under very general conditions time reversal and reciprocity symmetry. These universal symmetry properties may be exploited for efficient data transfer in scattering media. Recently this was demonstrated in an ultrasonic experiment probing the transfer matrix between multiple antennas in a strongly scattering medium [6].

The data transfer by elastic waves in a two-dimensional solid-state cavity is studied here experimentally. Robust time-reversal reconstruction of pulsed signals in a 2D chaotic cavity system has been demonstrated earlier [7], [8], [9]. In an irregular and slightly dissipative cavity strong mode mixing leads to multi mode coupling between any two points in the cavity. In particular if the shape of the cavity fulfills the criteria to form a classical chaotic system, time-reversal with one channel [7], modified enhanced back-scattering [8], and sub-wavelength focusing [9] has been achieved.

The multiple scattering in the cavity assists in decoupling signals from transducers further apart than typically a wavelength distance. I.e. the size the typical size of a speckle spot. Perfect time reversal behavior is only possible in a dissipation free system. However, even in systems with dissipation reversibility is partially maintained. Furthermore, the dissipation is essential for efficient data transfer to avoid saturation of the emitted signal.

Method

The concept of time reversed coding and the use in data transfer is demonstrated here in a chaotic cavity consisting of a 0.35mm thin 76mm diameter silicon wafer [7], [8], [9], [10]. Arbitrary modulated compression waves at ≤ 1 MHz are generated and detected by ultrasonic transducers connected to sharp needles that act as point-like transmitters and receivers (see figure 1) [11]. A typical experimental recorded signal is shown in figure 2. A single cycle excitation (left) results in a strongly dispersed arriving pulse (right) and a long lasting 'coda' build up by multiple reflections inside the wafer. In addition, the transfer from the needle to the ultrasonic transducers also causes dispersion. The reverberation time t_r in the cavity is in the millisecond range.

The strong mode mixing between the lamb modes and the shear horizontal modes in the thin wafer and

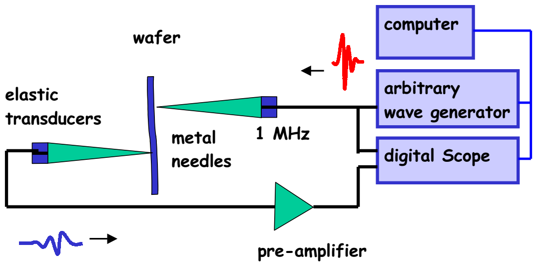

Figure 1: Schematic set up for quasi two-dimensional ultrasound experiments in a Silicon wafer. Arbitrary modulated compression waves at ≤ 1 MHz are generated by an ultrasonic transducer (Panametrics V103-RM) with a computer controlled wave generator (HP 33120A). The transmitted waves are detected by a similar ultrasonic transducer, pre-amplified (EG&G 5113) and recorded on a digital oscilloscope (Tektronix TDS440).

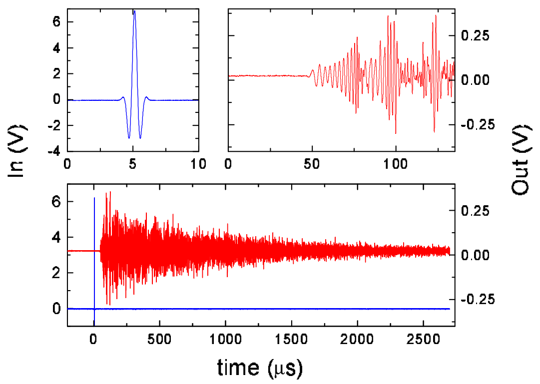

Figure 2: Recorded signal after excitation with a short pulse (blue curve) shows strongly dispersed first arrival and a millisecond relaxation (red curve). On the top details of the transmitted and received pulse are shown.

the strong anisotropy of silicon is not destroying the time reversal and reciprocity symmetry in the system. An example of a time reversal reconstruction is shown in figure 3.

The reconstruction was obtained by exploiting reciprocity in the system and use the same transmitter and receiver configuration for the recording and the reconstruction. A detail of the reconstructed pulse is shown in figure 3. The signal is symmetric around the reconstruction maximum at 2.69 ms. This indicates that before and after the reconstruction the contributing frequencies are gradually changing their relative phase until they are fully de-correlated. Hence, the apparent noisy background in the reconstructed signal is not noise, but is an essential part of the reconstruction. For the time reversed reconstruction only a small section of the recorded signal is necessary. As long as the frequency content of that section is enough to represent the transmitted pulse [12].

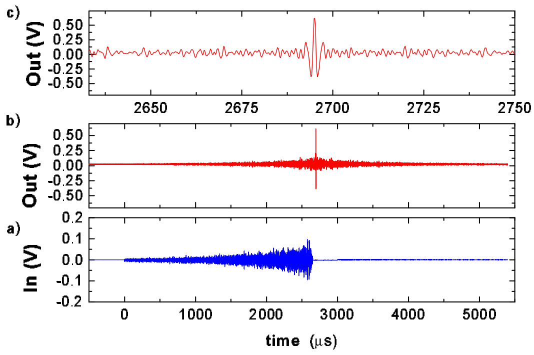

Figure 3: Time reversal reconstruction (b,c) using part of the recorded signal (a). The transducers were separated by 4 mm.

Time-reversed keying

Signals represented by a stream of pulses separated by a fixed relative delay dt will be strongly dispersed when transmitted. The overall received signal is the convolution of the pulsed input stream with the response to a single pulse as shown in figure 3. Any pulse sequence with dt shorter than the reverberation time t_r will be difficult to decode by e.g. threshold detection.

Once the impulse response is recorded, deconvolution of the signal would be possible at the receiver side in the form of an adaptive deconvolution filter. A more attractive alternative is time-reversed coding of the signal at the transmitter. A small section of the recorded pulse response is time-reversed and used as a key. The pulse stream is coded by adding time shifted copies of the key and than transmitted. The receiver will obtain a reconstructed pulse stream with a contrast between pulse and background suitable for threshold detection. An example for a double pulse signal is given in figure 4. A section of 2000 points is used as the key with a relative delay of 2500 points (top of figure). The received signal shows the reconstructed double pulse on top of the interference background.

Figure 5 illustrates the reconstruction for different time delays dt. At the smallest separation of $dt = 5\mu$s, the pulses are still resolvable.

By using time reversal coding of transmitted signals, data rates well in excess of the inverse of the reverberation time are achieved. The minimum detectable separation was ≈ 25 points corresponding to 2 oscillations. In comparison with the reverberation time of 2500 points, this is an increase by a factor of 200. In a data stream the performance is less due to the fact that the residual reverberation signals of all previous pulses is contributing to the background signal.

The time reversal reconstruction is specific for one place in the cavity. The area corresponds to the size of the speckle generated by the multiple scattered sound

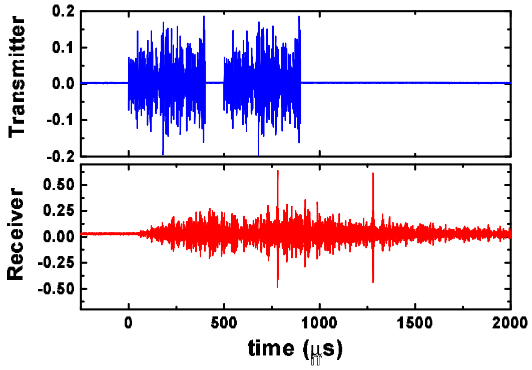

Figure 4: Double pulse with a relative delay of $dt = 500\mu$s is coded by adding the key of $\Delta T = 400\mu$s or 2000 recorded points from the time-reversed recorded signal. Top (blue) the transmitted signal. Bottom (red) the received signal.

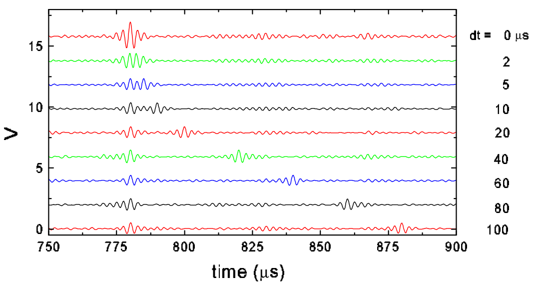

Figure 5: Reconstruction of a double pulse for different time delays dt using the same key as in figure 4.

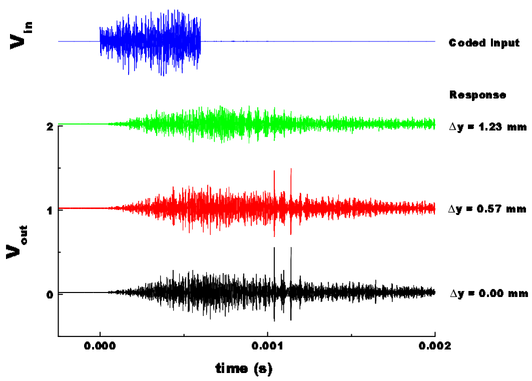

Figure 6: Reconstruction of a double pulse for different separation y between receiver and transmitter needle using the same key recorded at a separation of $y = 10$ mm ($\Delta y = 0$ mm). Key length $\Delta T = 1$ms, separation $dt = 0.2$ms.

and is typically in the order of a wavelength in diameter. Figure 6 illustrates the spatial dependence. When the needle separation is increased by less than a mm, the reconstruction is already lost completely. The spatial dependence of the reconstruction has e.g. been applied in target specific underwater communication with acoustic arrays[13]. The spatial decorrelation can be used to implement multiple input multiple output (mimo) schemes [6].

A more quantitative analysis of the pulse discrimination can be performed by using the concepts of a 'correlator receiver' where the position of the received pulses in a bit stream is assumed to be known [14]. These concepts are used when gaussian noise is added in the data transfer. In binary pulse amplitude modulation (PAM) coding with two key signals $s1(t)$ and $s2(t)$ the acceptance criterium for reception of a particular signal in a received signal $y(t)$ is obtained by calculating $Q =< y(t).v(t) >$, where $v(t) = s1(t) - s2(t)$ and the averaging operation $< . >$ is over the separation dt. By choosing $s1 = -s2$, the two keys are orthogonal: i.e. $< s1.s2 >= 0$. Then the coding is equivalent to phase modulation The criterium is that for $Q > 0$, signal $s1$ and $Q < 0$, signal $s2$ is accepted.

The performance of time-reversal coded signals using a 'correlator receiver' principle is illustrated in figure 7. The keys $s1$ and $s2$ are generated by adding a large cosine series with frequencies randomly chosen from an interval. The received signals are simulated by using only a few terms from the same series. A reference signal is generated by using the same cosine series with a random phase. The correlation performance is illustrated in figure 7.b as an histogram. The correlation criterium clearly separates the two signals and the equivalent noisy reference. Other coding schemes based on phase shift or amplitude keying [5] can easily be implemented as well. The test shown here only use coding of two pulses. To sustain a high capacity bitstream, the minimum separation between pulses has to be enlarged.

Conclusion

By using time-reversal coding and the ability to concentrate decoded pulses in the time domain, enhancement data transfer is feasible.

Acknowledgements

The author would like to thank A. Tourin, J. de Rosny and M. Fink from the ESPCI in Paris for the discussions about the 2D acoustic experiments. This work is part of the research program of the "Stichting voor Fundamenteel Onderzoek der Materie (FOM)" (Foundation for Fundamental Research on Matter), which is

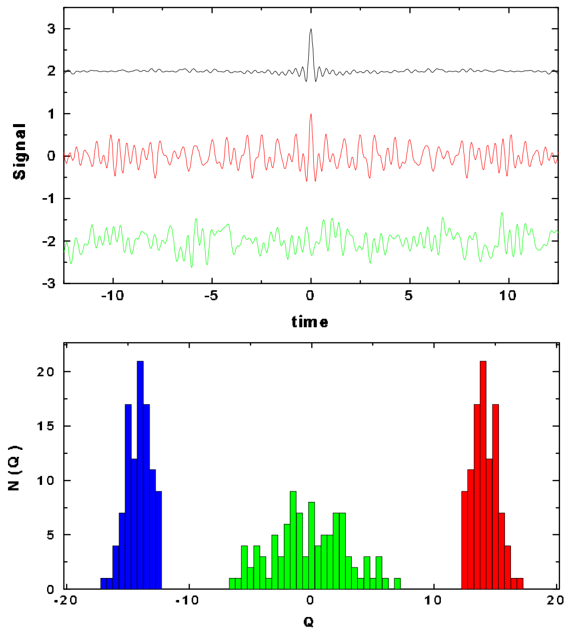

Figure 7: Simulation of correlation receiver performance using key signals $s1$ and $s2$ generated by adding 1000 $cos(2\pi ft)$ terms with f randomly chosen from the interval (0.1, 2.9) ($s1$, top, black). The received signal $y(t)$ is generated by choosing only 10 frequencies (top, red). The reference signal is 10 frequencies and random phase (top, green). The correlation $Q =< y(t).(s1(t) - s2(t)) >$ for 200 realization of $y(t)$ is shown as a histogram (bottom). The blue, red, and green curve are for $s1$, $s2$, and reference signal realizations respectively.

financially supported by the "Nederlandse Organisatie voor Wetenschappelijk Onderzoek (NWO)" (Netherlands Organization for the Advancement of Research).

References

[1] S. H. Simon, A. L. Moustakas, M. Stoytchev, H. Safar, "Communication in a Disordered World", Physics Today, Vol. 54, pp.38-43, 2001.

[2] A. L. Moustakas, H. U. Baranger, L. Balents, A. M. Sengupta, S. H. Simon, "Communication Through a Diffusive Medium: Coherence and Capacity", Science, Vol. 287, pp. 287-290, 2000.

[3] C.E. Shannon, "A mathematical theory of communication", Bell Syst. Tech. J., Vol. 27, pp. 379 and 623, 1948.

[4] G.J. Foschini, "Layered space-time architecture for wireless communications in a fading environment when using multiple antennas", Bell Tech. J., Vol. 1, pp. 41-59, 1996; G.D. Golden, C.J. Foschini, R.A. Valenzuela, P.W. Wolniansky, "Detection algorithm and initial laboratory results using V-BLAST space-time communication architecture", Electronic Letters, Vol. 35, pp. 14-16, 1999.

[5] T.S. Rappaport, 'Wireless Communications: Principles and Pratice', 2nd Ed., Prentice Hall, Upper Saddle River, NJ, 2002.

[6] A. Derode, A. Tourin, J. de Rosny, M. Tanter, S. Yon, M. Fink, "Taking Advantage of Multiple Scattering to Communicate with Time-Reversal Antennas", Phys. Rev. Lett., Vol. 90, pp.014301-1:4, 2003.

[7] C. Draeger, M. Fink "One-channel time-reversal of elastic waves in a chaotic 2D-silicon cavity", Phys. Rev. Lett., Vol. 79, pp. 407-411 1997; ibid., "One-channel time-reversal in chaotic cavities: Theoretical limits", Journal of Acoustical Society of America, Vol. 105, pp. 611-617, 1999.

[8] J. de Rosny, A. Tourin, M. Fink, "Coherent backscattering in a 2 D chaotic cavity", Phys. Rev. Lett., Vol. 84, pp. 1693-1697, 2000.

[9] J. de Rosny, M. Fink, "Overcoming the Diffraction Limit in Wave Physics Using a Time- Reversal Mirror and a Novel Acoustic Sink", Phys. Rev. Lett., Vol. 89, pp. 124301-1:4, 2002.

[10] R. Sprik, A. Tourin, J. de Rosny, M. Fink, "Data Transfer by Elastic Waves in Dissipative Irregular Cavities using Time Reversed Coding", submitted to Appl. Phys. Lett.

[11] F. L. Degertekin, B. T. Khuri-Yakub, "Lamb wave excitation by Hertzian contacts with applications in NDE", IEEE Trans. Ultrason., Ferroelect., Freq. Contr. Vol. 44, pp. 769-779, 1997.

[12] R. Sprik, A. Tourin, "Time reversed wave propagation experiments in chaotic microstructured cavities", Ultrasonics International 2003, Grenada, Spain, 1-3 july 2003.

[13] W. A. Kuperman, William S. Hodgkiss, Hee Chun Song, T. Akal, C. Ferla, Darrell R. Jackson, "Phase conjugation in the ocean: Experimental demonstration of an acoustic time-reversal mirror", J. Acoust. Soc. Am., Vol. 103, pp. 25-40, 1998.

[14] W.C. Lindsey, M.K. Simon, 'Telecommunication Systems Engineering', Dover Publications, New York, 1991.