Optical waveguide amplifier in Nd-doped glass written with near-IR femtosecond laser pulses

Y. Sikorski, A.A. Said, P. Bado, R. Maynard, C. Florea and K.A. Winick

A near-IR (775nm) femtosecond laser has been used to directly write a 1cm long optical waveguide in Nd-doped silicate glass. A gain of 1.5dB/cm was obtained at a signal wavelength of 1054nm for ~346mW of 514nm pump power, in front of the input coupling objective.

Introduction: It is well known that the properties of glass can be changed by exposure to light. The discovery by Hill [1] of the photosensitivity of silica fibres at UV wavelengths and the extension of this method by Meltz [2] to a direct-writing technique using a holographic setup has had a major impact on guided wave device development. The UV direct-write method has been used to write gratings in planar waveguides and optical fibres and even to directly write waveguides in bulk glasses [3]. This method, however, has inherent limitations. In particular, many glasses are not sufficiently sensitive to yield significant changes in refractive index on exposure, and hence UV direct writing has been primarily used for high-purity germanosilicate glasses. Also the UV photosensitivity band is very close to the absorption edge of most glasses, and thus the UV penetration depth is small. This fact has precluded the use of UV direct-write techniques to produce three-dimensional structures in bulk glasses. Recently it has been demonstrated that near-IR femtosecond laser pulses can be used to induce localised refractive index increases in a wide variety of glasses [4]. Thermally stable optical waveguides were reported in 1997 by Miura *et al.* [5] in silicate, borosilicate, chalcogenide and fluoride glasses. Also, more complex structures such as a Y-junction splitter [6] and long period gratings [7] have been produced.

In this Letter we present for the first time, to the best of our knowledge, an active waveguide device directly written using near-IR femtosecond laser pulses. The device is a waveguide amplifier in Nd-doped silicate glass.

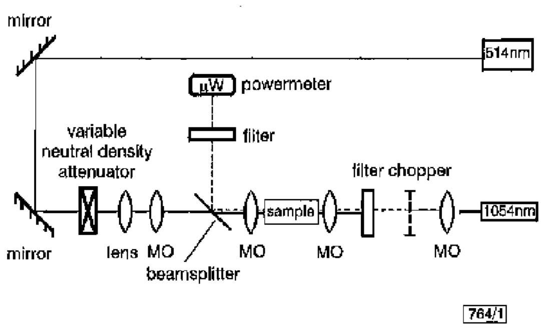

Fig. 1 *Gain measurement setup*

MO: microscope objective

Experimental details: The material used in this study was a commercially available Nd-doped silicate glass rod with a diameter of 0.5inches. We measured the absorption coefficient of the glass using a spectrophotometer and we found a maximum value of $4.6cm^{-1}$ at 806 nm. Using this value together with typical absorption cross-sections for Nd-doped silicate glasses, we estimate the Nd doping level to be $\sim 2 \times 10^{20}$ ion/cm^3. We also recorded the fluorescence spectrum, using an optical spectrum analyser, when the bulk sample was pumped at a wavelength of 806nm. The peak was in the vicinity of 1062nm.

For waveguide fabrication a femtosecond Ti:sapphire laser operating at 775nm, with a pulsewidth of 150fs, a 250Hz repetition rate, and a 4μJ pulse energy was used. The waveguide was written in a piece of glass rod of ~1cm length which had its ends optically polished. The laser beam had a $1/e^2$ intensity full-width of 3.3mm × 3.9mm, and was focused with a lens of 15mm focal length inside the sample. The focus was scanned at a rate of 25μm/s along a direction parallel with the beam. A total of five scans were made along the same path. After the writing was completed, the end faces of the sample were polished until the ends of the waveguide reached the surface. The near-field mode profile was collected at 632.8nm using an unpolarised He-Ne laser and a CCD array.

For amplifier characterisation, gain measurements were performed using an Ar ion pump laser as a source at 514nm and a signal at 1054nm provided by a fibre laser. We used a counter-propagating geometry (Fig. 1) in which the pump beam is launched in the waveguide by end-firing through one end and the signal is also end-fire coupled but through the other end. The launched signal power levels were of the order of 300μW. The signal beam was chopped and the changes were recorded as the pump beam was turned on and off for a few different levels of pump power.

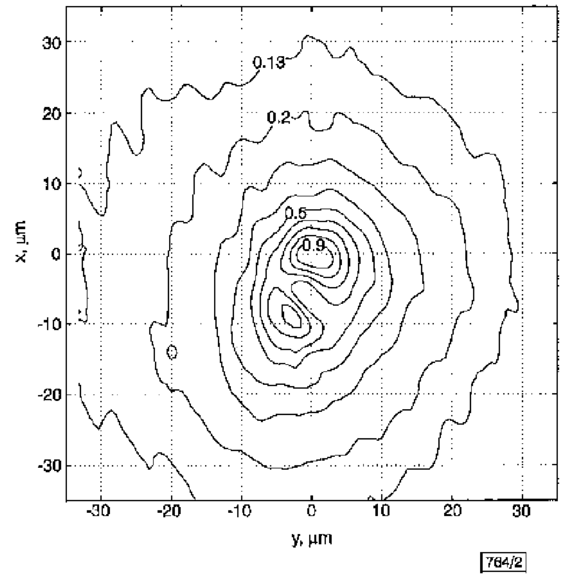

Fig. 2 *Contour plot of normalised intensity near field mode profile*

Results and discussion: An intensity contour plot of the near-field mode profile at 632.8nm is shown in Fig. 2. Although this mode profile is not single-lobed, we have also obtained singlemode profiles using slightly different writing conditions. Further characterisation of these devices, including loss measurements and a thermal stability study, is in progress.

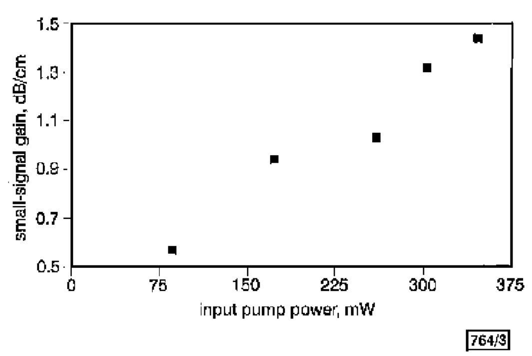

Fig. 3 *Signal gain against input pump power*

The data on the gain of the amplifier for a 1054nm signal are presented in Fig. 3. The gain was measured as the ratio between the signal power with the pump turned on and the signal power with the pump turned off. The pump power was measured in front of the input coupling objective and preliminary estimates indicate a coupling efficiency of 20–40%. To verify that the change in the signal power is not due to some thermal effects, the experiment was repeated using the 488nm line of the Ar ion pump laser. The fact that no gain was observed, as expected, since Nd does not have a 488nm absorption band ruled out the influence of thermal effects. Fluorescence data indicate that the emission cross-section at 1054nm is only half as large as that at the 1062nm peak. Thus this device exhibits a gain of ~3dB/cm for input pump power levels of ~350mW. This amount of gain should be sufficient to support lasing, provided that high reflectors are affixed to the ends of the waveguide. Experiments for achieving lasing are in progress.

Conclusions: We have optically written a 1cm long waveguide amplifier in Nd-doped silicate glass using near-IR (775nm), 150fs, 250Hz repetition rate, 4μJ laser pulses. A gain of 1.5dB/cm was measured at 1054nm when the device was pumped with ~350mW at 514nm.

Acknowledgments: This work was supported by the Department of the Air Force under the contract F29601-99-C-0044 and additional funding was provided by the NSF through grant #ECS-9522200.

15 December 1999
Electronics Letters Online No: 20000172
DOI: 10.1049/el:20000172

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Generalised Viterbi algorithm for trellis coded signals transmitted through broadband wireless channels

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A receiver structure is proposed for trellis coded signals transmitted through broadband wireless channels based on the generalised Viterbi algorithm (GVA). Simulation results show that the proposed receiver structure is suitable for high bit rate wireless applications and gives close to optimal performances with reasonable complexity.

Introduction: The optimal way to decode trellis encoded signals transmitted along intersymbol interference (ISI) channels is to use the maximum likelihood (ML) 'supertrellis', a combination of ISI and code trellises, the state complexity of which is the product of both [1]. Unfortunately, for frequency selective radio channels, the number of states of the ISI trellis increases exponentially with the bit rate, which precludes this approach for broadband wireless radio interfaces. As a consequence, a lot of work has been done on sub-optimal receivers for trellis coded modulation (TCM) in the presence of ISI [1 – 4]. In [1], a systematic method is developed for lowering the state complexity of the supertrellis. An interesting case arises when the receiver trellis is reduced to the code trellis [1 – 4], the complexity of which does not depend on the bit rate. The ISI due to the channel is not taken into account in the trellis states but in the edge metric, as done in a classical decision feedback equaliser (DFE). It follows that such a receiver, commonly known as parallel decision feedback decoding (PDFD), inherently suffers (as does the DFE) from error propagation, especially in the case of non-minimum phase channels. Therefore, the PDFD receiver requires pre-filtering to turn the channel into minimum phase. This pre-filtering is cumbersome and increases the overall receiver complexity. Besides, error propagation still remains.

In parallel, many efforts have been devoted to improve sub-optimal equalisation techniques for broadband wireless channels. Once again, the issue is the complexity of the ML ISI trellis. In [3, 5] a method is proposed to reduce the ML ISI trellis. In [5, 6], it is shown that the generalised Viterbi algorithm (GVA), which retains more than one survivor per state, is a very efficient algorithm for combatting error propagation.

The proposed receiver combines the PDFD algorithm with the GVA. Simulations prove that the GVA makes the PDFD receiver very robust to error propagation (even in the case of non-minimum phase channels) for a reasonable complexity increase. It is even shown that in most cases the ML optimal performances are attained with only four survivors per state.

In the context of packet wireless transmissions, granularity constraints do not allow interleaving on more than one cell. Since the proposed method does not require any kind of interleaving, it is a perfect candidate technique for such transmissions.

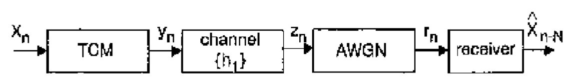

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Fig. 1 *Structure of discrete time equivalent communication chain*

Proposed algorithm: The discrete time equivalent structure of the proposed communication chain is shown in Fig. 1. The data signals are transmitted in bursts including N coded data symbols and a known training sequence used both for channel estimation and algorithm initialisation. Tail bits are added to close the trellis into the all-zero state. Let the estimated (symbol spaced) impulse response of the convolution of the transmitter filter, the receiver filter and the radio-mobile channel, be denoted as

$$\{h_l\} \qquad l \in [0, L]$$

The overall channel does not need to be minimum phase, but the receiver filter should ensure that the noise samples at the symbol rate are uncorrelated at its output, as is the case for a root raised cosine filter, for example. The output of the received filter at timing instant $t = n$ is then

$$r_n = h_0 y_n + b_n + I_n$$

where y_n is the current coded data symbol to be received, $I_n = \Sigma_{l=1}^{L} h_l y_{n-l}$ is the ISI term in the nth timing instant, and b_n is a Gaussian noise sample. Note that the decoder trellis can be derived from a convolutional code, a TCM or a block code. In this respect, the general case of a time variant Markovian process is considered in the following. The coded data symbol y_n is related to the incoming bits $\{x_n\}$ by a time variant relationship (including coding and bit mapping) of the form

$$y_n = f_n(x_n, x_{n-1}, \ldots, x_{n-K_n})$$

We assume that the decoder trellis section at time $t = n$ has V_n vertices and E_n edges (including parallel transitions for TCM). The trellis vertex and edge complexities are respectively

$$V = \sum_{t=0}^{N} V_t \quad \text{and} \quad E = \sum_{t=1}^{N} E_t$$

The PDFD algorithm estimates the ML metric

$$\sum_{t=1}^{N} \left| r_n - h_0 y_n - \hat{I}_n \right|^2$$

on the decoder trellis, where $\hat{I}_n$ is the estimated ISI calculated as a DFE using a traceback array T of size V that saves the path lead-