A photonic switch based on a gigantic, reversible optical nonlinearity of liquefying gallium

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Abstract

Liquefying gallium shows a huge reversible optical nonlinearity which is compatible with waveguide technology and promises to be a breakthrough in broadband, light by light modulation at milliwatt operating power levels and frequency band spanning up to several hundred kilohertz.

Over the past few years it has become apparent that the frequency degenerate cubic optical nonlinearities of metals such as gold, copper, silver, indium and nickel reach rather high values, of the order of ~10^{-8} esu [1-2]. The nonlinear response of metals is in general broadband and in most cases occurs on a femtosecond time scale. Unfortunately, despite the large nonlinear coefficients, the light penetration depth and corresponding effective nonlinear interaction lengths are only a few tens of nanometers, resulting in total nonlinear responses that have been too small for applications concerning control of light by light. However, recently we saw that an enhanced nonlinear response can be obtained in indium in the proximity of a structural phase transition: the cubic nonlinearity of indium increases nearly ten-fold at its melting point to c value of 10^{-7} esu [3]. Subsequent to this we made the remarkable observation [4] that the reflectivity of a gallium-glass interface can be modified by as much as 30% by continuous-wave optical stimulation at an intensity of only a few kW/cm^2, if the temperature is held just below the metal's melting point (~30°C). This represents an optical nonlinearity in excess of 10^{-1} esu. However, these early experiments were performed with unmodulated optical excitation and no dynamics of the optical response has been studied.

In this letter, we report on the initial experiments on the reversibility and temporal dynamics of optical nonlinearity in gallium. Our experiments show that the mechanism underlying the massive optical nonlinearity of gallium in the vicinity of its melting point is fully reversible. In the course of this research we have developed a fully fiberised, all-optical switch which operates at a wavelength of 1550nm, requires only a few mW of switching power and provides ~30% switching contrast.

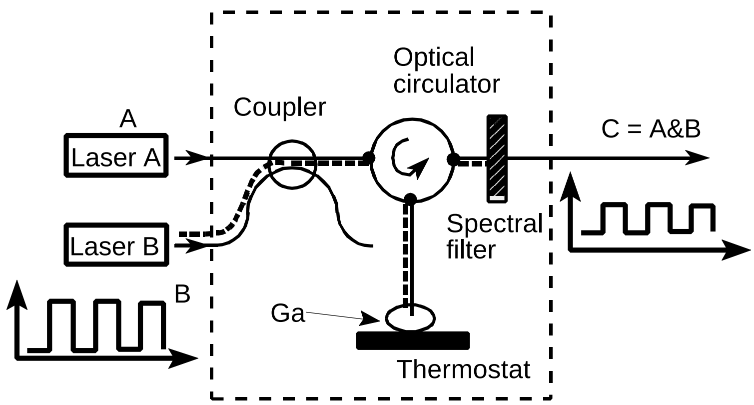

Fig. 1 Schematic of the pump-probe experiment on the nonlinearity of liquefying gallium using a fiberised optical switch.

The nonlinear response of liquefying gallium was characterized in pump-probe experiments using the optical switch set-up shown in Fig.1. The pump source B was an amplified continuous-wave, narrow linewidth (~10kHz), external-cavity diode laser operating at 1536nm. The source was externally modulated using an acousto-optic Bragg cell. The pump was filtered with a 3GHz fibre Bragg grating to eliminate amplifier noise and then combined with a continuous probe using a fiber coupler. The pump pulses were monitored at the fourth port of the coupler. The probe source A was a continuous-wave DFB diode laser operating at λ = 1.550μm and had 1MHz linewidth. The pump and probe beams were coupled onto and off of a gallium mirror using an optical circulator.

The fibre mode-field diameter was ~12 μm. The peak power of the pump pulses incident on the mirror could be varied between 0 and 8mW, while the power of the continuous wave probe beam was

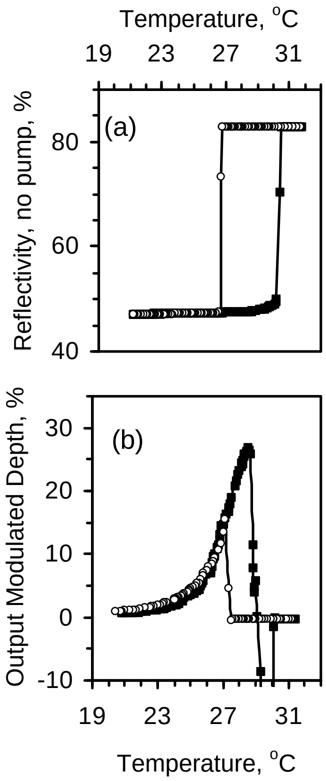

Fig. 2a) Reflectivity of a gallium-silica interface at low light intensity as a function of temperature, near the melting point, illustrating a strong change of reflectivity, overcooling and a reflectivity hysteresis;

2b) Output probe intensity modulation depth as a function of temperature for a pump with 50% duty cycle, frequency of 500Hz and 5mW peak power.
On figures a) and b) symbols # denote the heating cycle while symbols # denote the cooling cycle.

60 μW at the mirror surface. The probe beam was separated from the pump beam at the circulator output using a (tunable) 2nm band pass, dielectric filter which suppressed the pump beam at the output by more than 20dB relative to the probe. In most of the experiments reported herein the probe beam was detected at the switch output C with a InGaAs photo diode with a high- gain preamplifier of 250 kHz 3dB bandwidth. The fiberised gallium mirror was formed by immersing the freshly cleaved end of a single-mode silica optical fiber into a small bead of initially molten gallium of 5N purity. The sample temperature was controlled by a miniature Peltier heat pump to a precision of 0.01 °C at temperatures around the melting point of gallium.

Initially we examined the linear reflectivity of gallium at temperatures around its melting point using the probe beam only. As has already been seen on a free surface of gallium [5], at the gallium-silica interface heated and cooled across the melting point we observed a pronounced reflectivity hysteresis associated with supercooling (see fig.2a). The reflectivity of gallium in the solid phase is about 50% but this rises abruptly to approximately 90% on melting. The change in

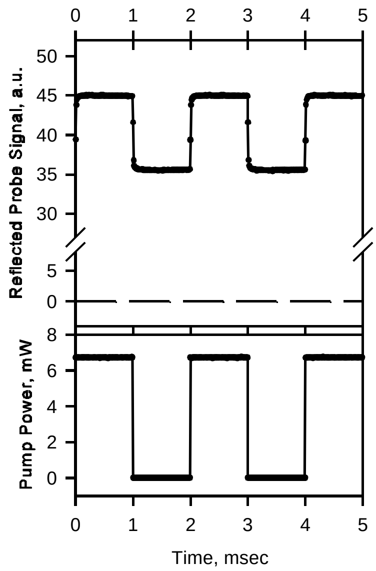

Fig. 3 Pump-probe modulation in fiberised optical switch: upper trace shows the output probe power as a function of time in the presence of a 7mW modulated pump (lower trace).

reflectivity is due to the partial destruction of covalent bonding character of the α-phase of solid gallium on melting resulting in more metallic properties for the molten gallium [6]. It should be mentioned that the α-phase is anisotropic and in experiments we always adjusted the probe beam polarisation to give minimum reflectivity in the solid phase. We next investigated the dynamic nonlinear properties of the mirror at temperatures in the vicinity of the melting point. In Fig.3 we plot the power of the probe beam at the output of the switch in the presence of the square wave modulated pump beam for a gallium mirror temperature ~3°C below the metal's melting point. The gallium bead was in the solid phase i.e. on the lower branch of the hysteresis curve shown in Fig.2a. Significant, fully repeatable ~25% pump-induced changes in reflected probe intensity are observed due to the presence of the ~7 mW pump pulses. These measurements are extremely important as they show that the induced reflectivity changes reported in Ref [4] are fully reversible. Moreover, since our earlier observations reported

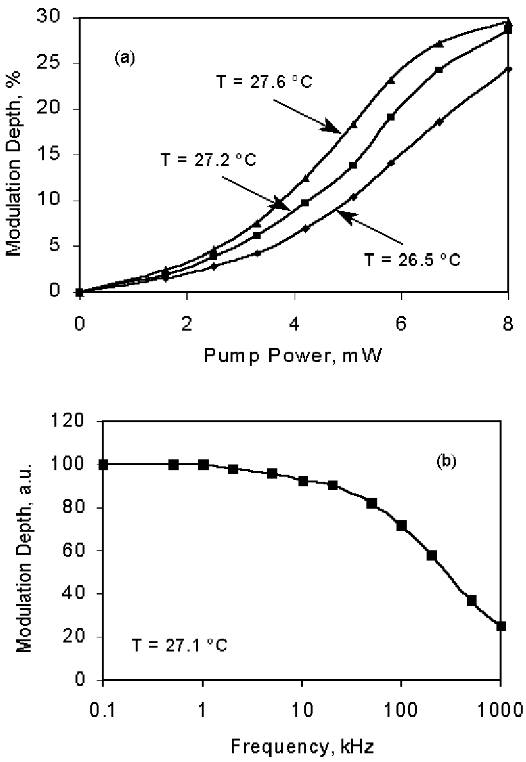

Fig.4 Output probe intensity modulation depth presented as a function of: (a) peak pump power for pump pulses at a modulation frequency of 500Hz, 100% modulation depth and 50% duty cycle at different sample temperatures; (b) pump modulation frequency at a fixed pump power of 8.0mW, 100% modulation depth and 50% duty cycle.

on [4] were made at a wavelength of 1260nm, the present experiments at wavelengths around 1550nm demonstrate that the effect is truly optically broadband.

We next measured the induced change in reflected probe intensity as a function of temperature. At low temperatures, below 20°C, the nonlinear response is fairly small, however as the temperature is increased towards the melting point the induced nonlinear response rises steadily up to a level of 30% as shown in Fig.2b. The modulation within this temperature region is highly stable and reproducible. However, at higher temperatures, just about 1.5°C below the bulk melting point the induced reflectivity falls rapidly and eventually changes sign. This is accompanied by a significant decrease in the absolute sample reflectivity and by significant probe pulse distortion. The induced modulation vanishes abruptly once the metal melts. On subsequent recooling the nonlinearity is fully restored as the gallium solidifies.

In Fig.4a we plot the intensity dependence of the induced change in reflected probe power for a number of temperatures in the proximity of the melting point. Once again the gallium bead was in the solid phase. We obsessed up to ~30% changes in the reflected probe intensity induced by the pump for pump powers of only a few mW. The pump power required to achieve such a modulation depth decreased as the temperature was increased towards the bulk gallium melting point. At powers substantially higher than those required to obtain the maximum nonlinear response at a given mirror temperature some distortion of the switched signal became apparent.

Finally, we varied the frequency of modulation of the pump for a fixed power (8mW) and duty cycle (50%) up to our systems upper frequency limit of 1MHz. In these experiments we replaced the 200Hz photodetector with a 1GHz 3dB bandwidth InGaAs detector. The observed 3dB bandwidth was ~200kHz, although useful modulation was still obtained at frequencies around 1MHz (see Fig.4b).

The exact microscopic mechanism(s) behind this surprisingly large optical nonlinearity are currently being investigated. Simple bulk melting due to light-induced heating has already been excluded because gallium shows supercooling on solidification and therefore any reflectivity change would be irreversible even then the light is withdrawn. Our current thinking is that the nonlinearity is due to a light-induced structural phase transition from the `ground state' α-gallium phase to some other more metallic, metastable phase or even molten state of higher reflectivity which relaxes back to the α-gallium phase once the

optical stimulation is removed. We believe that the reflectivity of the surface, which was seen to change continuously with pump intensity, depends on the depth of this layer's highly reflective phase of gallium. We are currently examining the possibility that the depth of this highly reflective gallium phase may be found from the thermodynamic considerations used in the theory of surface melting [7], and that the temporal dynamics of the nonlinear response is controlled by the velocities of the interface between α-gallium and the light-induced metastable phase [8].
The results of this research will be published shortly.

In conclusion, we have demonstrated that a gallium-silica interface shows a gigantic, broadband, reversible optical nonlinearity if the metal is held just below the bulk metal melting point. Up to a 30% modulation in reflected light intensity has been observed in a compact, fiberised switch at optical powers in the range ~1-8 mW. We consider this nonlinearity to offer tremendous potential for the development of a wide range of truly practical nonlinear optical devices compatible with existing waveguide technology.

The results reported in the present paper are covered by a patent application. [9].

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