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NONLINEARITY OF LIQUEFYING GALLIUM: CONTROLLING LIGHT WITH LIGHT AT MILLIWATT POWER LEVELS

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Abstract

Liquefying gallium shows a new type of huge reversible nonlinearity which is compatible with waveguide technology and offers a breakthrough in broadband, high-contrast light by light modulation at milliwatt power levels with sub-microsecond response times.

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Summary

We have recently demonstrated that the reflectivity of a metallic gallium - glass interface shows a strong change and a noticeable hysteresis in the melting-cooling cycle, and that such a hysteresis can be considerably modified by continuous wave optical stimulation at intensities of a few kW/cm^2 [1]. Here we demonstrate that the non-resonant nonlinear mechanism is fully reversible with a fast recovery time. This nonlinearity has been used to achieve a truly practical all-optical switch with milliwatt switching powers, submicrosecond response times which could be used from the visible to IR spectral regions.

The switch layout is illustrated in Fig.1. The radiation from two diode lasers operating at λ_A = 1550nm (probe beam, power =60μW) and λ_B = 1532nm (pump beam) is combined and coupled directly onto the interface between a small bead of gallium and the cleaved end of a single-mode optical fibre with mode area 120μm^2. The temperature of the gallium is maintained just below the melting point (~29 °C). The incident light is reflected back down the same fibre where it is separated from the incident radiation using an optical circulator. The probe beam is separated from the pump beam by a 1nm bandwidth dielectric filter at the switch output. Modulation of the pump beam intensity induces a reflectivity change at the gallium-glass interface inflicting modulation on the probe intensity. We examined the switch response to pump modulation whilst varying the duty cycle, frequency and power (see figures 2-3). We found that for continuous modulation the switch can operate at frequencies exceeding 100kHz and can cope with sub-microsecond pulses.

The physical mechanism behind this surprisingly large optical nonlinearity is currently not completely understood. However, it is definite that it is not a thermal effect because the high latent heat of melting in gallium would require approximately five orders of magnitude more light power to achieve light-induced melting than in our experiments. Also a thermal nonlinearity could not be reversible due to the pronounced supercooling effect. Although the melting transition of bulk crystals is strongly first order in nature, the situation is different in the presence of an interface with another material, optical glass in our case. There is strong theoretical and experimental evidence for believing that the melting of gallium at an interface is continuous (surface melting), with associated critical behavior. Therefore, for reflected light which interacts with only few atomic layers, liquefaction of gallium may be seen as going through a second-order phase transition to a sub-liquid phase which is strongly confined to fixed adsorption sites on the substrate. Here the appearance of the giant optical nonlinearity may be interpreted as critical enhancement of the material susceptibility in the proximity of a second-order phase transition.

We consider this nonlinearity to offer tremendous potential for the development of a new range of truly practical nonlinear optical devices.

References

[1] S.Dhanjal, I.R.Shatwell, Yu.P.Svirko, N.I.Zheludev, 'Giant nonlinearity and reflectivity hysteresis in metallic gallium at melting', Paper QFF6, QELS'97, Baltimore, USA.

Figure captions

Fig. 1

Schematic of fiberized optical switch utilizing the nonlinearity of liquefying gallium.

Fig. 2

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

b) Output probe intensity modulation depth as a function of temperature for a pump with 50% duty cycle, frequency of 500Hz and 4.7mW peak power. An output modulation of around 30% is obtainable at temperatures close to the melting point.

Fig.3

Affect of the pump modulation upon the output probe intensity with

a) 50% duty cycle of pump modulation at 10kHz;

b) Switch response to 15-100ns pump pulses of 70 mW peak intensity indicates that a sub-microsecond response time can be achieved.

Fig. 1

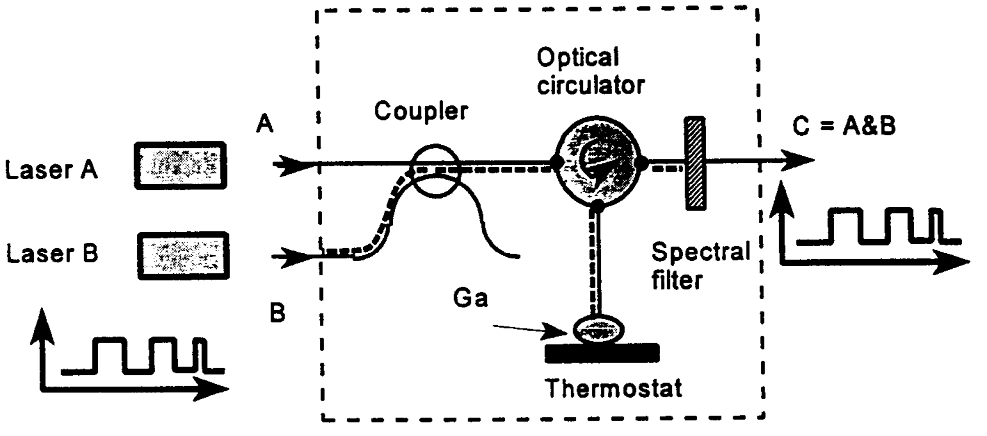

Laser A
Laser B
A
B
Coupler
Optical
circulator
Ga
Thermostat
Spectral
filter
C = A&B

Fig. 2

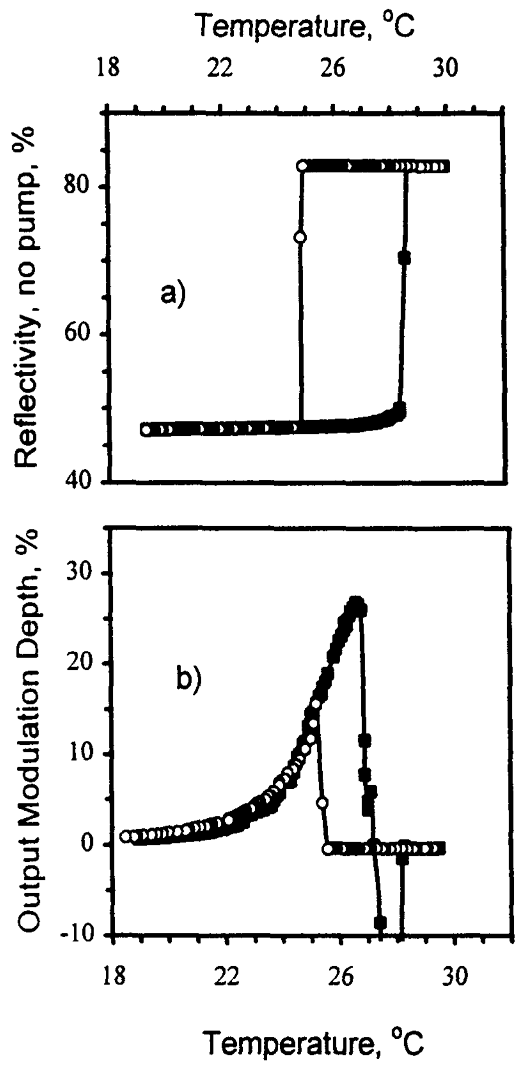
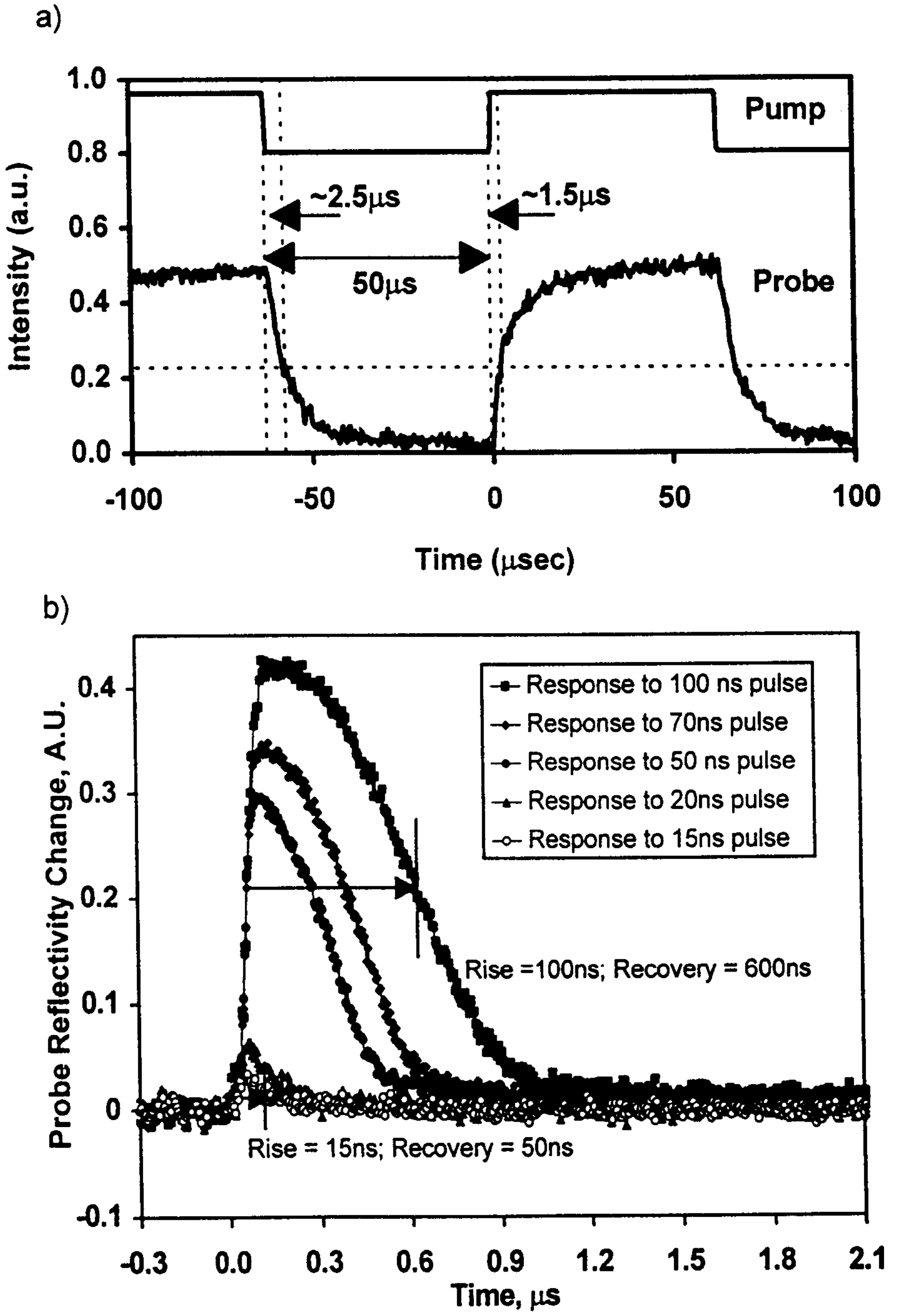

Temperature, °C
18
22
26
30
Reflectivity, no pump, %
80
60
40
a)
Output Modulation Depth, %
30
20
10
0
-10
b)
18
22
26
30
Temperature, °C

Fig. 3


a)
1.0
0.8
0.6
0.4
0.2
0.0
Intensity (a.u.)
Pump
Probe
~2.5μs
~1.5μs
50μs
-100
-50
0
50
100
Time (μsec)
b)
0.4
0.3
0.2
0.1
0
-0.1
Probe Reflectivity Change, A.U.
Response to 100 ns pulse
Response to 70ns pulse
Response to 50 ns pulse
Response to 20ns pulse
Response to 15ns pulse
Rise =100ns; Recovery = 600ns
Rise = 15ns; Recovery = 50ns
-0.3
0.0
0.3
0.6
0.9
1.2
1.5
1.8
2.1
Time, μs