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Optical switching properties of VO_2 films driven by using WDM-aligned lasers

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Abstract

Vanadium dioxide (VO_2) film had been demonstrated a high speed IR shutter driven by total optical modulation. However, it usually required a higher power heating laser of high power and precise optical systems to cover the probe beam on the sample with a heating beam of larger area. A new optical system, simply composed of wavelength division multiplexing (WDM), fiber lens or convex lens system, and a glass sheet with VO_2 thin film on it, was easily assembled to utilize VO_2 film as an IR shutter, implying the possibility to highly miniaturize the VO_2-based optical shutter. A permanent low-transmittance (PLT) region forms on the film within the probe beam, resulting in a decrease in average power of the probe beam. Another ring-type switching area (switching ring) forms around the PLT region, resulting in the transmittance switching of the probe beam synchronously with the heating signal. VO_2 films can be switched with the highest rate of a continuous square heating signal of 3 mW at 120 kHz. A heating pulse of 0.7 ns and 13 mW can be used to stimulate an IR pulse with fiber lens.

Keywords: Optical switch; IR shutter; VO_2; WDM; Vanadium dioxide

1. Introduction

Vanadium dioxide (VO_2) has been demonstrated as a high speed IR shutter, upon thermal cycling around typical phase change temperature 68°C [1,2]. One way to create thermal cycling of VO_2 film is by electrical heating directly on VO_2 film or indirectly through substrate or a metal heater [3–9]. The slow heating and dissipating efficiency of the heater limits the switching rate of the VO_2 shutter. In order to lower power consumption by electric heating, reducing the area of reactive VO_2 film increases the difficulty to align the focused probe beam on the small switching area. Higher absorption of visible laser by VO_2 film has been demonstrated for high speed heating of VO_2 [10–14]. A laser pulse of 35 ns at the wavelength 600 nm with power density of 6 mW μm^{-2} was reported to produce an IR pulse about 300 ns at the wavelength of 3.39 μm [13]. The difficulty of optical heating is to superimpose the heating region on the probe beam. To ensure the coverage of the switching region upon the probe region, a precision focusing system or high power laser used to produce large switching area are critical issues of total-optical-modulated VO_2 IR shutter. For example, if the area of a probe beam is 1 μm^2 on the sample, it is difficult to focus heating beam of spot size just a few μm^2 onto the probe beam. On the other hand, to create a large heated area without using an expensive focus system requires large power consumption.

This study aims to measure the dynamic response of VO_2 by a totally optical modulation with an easy-installed optical system and a heating laser source of low power consumption and low cost and, furthermore, to utilize VO_2 as a high speed IR shutter. Straightforwardly, to constrain both beams propagating in the same optical path ensures the overlap of projected area of both beams on the sample. The refractive indices of some glasses used in optical lenses are almost the same between wavelengths 600 and 1600 nm. For example, the refractive index of BK 7 glass at 650 and 1550 nm are 1.5132 and 1.5007, respectively. The small difference

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of refractive indices between both wavelengths results in small deviation of focal points of both beams passing through lenses. Combination of co-axial propagations and nearly confocal focusing system makes possible the integration of a VO_2-based IR shutter, which is compact and low power consumption. On the other hand, the working principle "whenever the focused heating beam writes is the switching area" also eliminate the difficulty to align focus probe beam on small switching area by electric heating.

2. Experimental

All films were prepared by a rf sputtering method sputter system. The Si thin film was prepared from a Si target of 3-in. diameter with a sputtering power 250 W. The gas pressure of Ar was kept at 3 mTorr during Si deposition. VO_2 films were prepared from V_2O_5 target by rf-magnetron sputtering with a target of 2-in. in diameter in another chamber under gas pressure of 30 mTorr [15]. Well-cleaned Corning 7059 glass was used as the substrate, which was kept at 400 °C by irradiation lamps during VO_2 fabrication. The sputtering power was kept at 90 W, under an oxygen flow ratio (R_{fo}) of 0.04, where $R_{fo} = f_{O_2}/(f_{O_2} + f_{Ar})$ and f is the flow rate of the gas in sccm. The sample measured in the study is mainly VO_2 film of 200 nm thickness sandwiched by a Si film of 130 nm on the top of Corning 7059 substrate.

The IR shutter is composed of two parts. The first part is used to constrain the propagations of both beams, followed by the optical lens system used to focus both beams onto the sample. The apparatus of the VO_2-based IR shutter is shown in Fig. 1a and b. Red diode laser of a wavelength 650 nm, often used in DVD pickup-head, was chosen as a heating source because of its low cost, high switching rate and good reliability. The probe laser of 1550 nm and a heating laser of 650 nm originated from a tunable laser and an optical disk tester (TUI tester), respectively. A wavelength division multiplexing (WDM) device, often used to collect many light beams propagating in the same fiber in optical communication, was used to guide both beams propagating in the same optical path. As shown in Fig. 1, the heating beam was coupled into one input end of WDM device. A fiber from tunable laser was connected to another input end of WDM with an FC/PC connector, ensuring that the probe beam could effectively enter the fiber of WDM device. A convex lens system or fiber lens was used to focus both divergent beams on the sample, after both beams pass through the WDM device. As shown in Fig. 1b, a silica rod of about 400 μm, connected to the output end of WDM, was fused to form a convex lens instead of focusing lenses system shown in Fig. 1a. Behind the sample, a thin silicon sheet, in front of the photo-detector, was used to stop the heating beam to illuminate onto the IR photo-detector. A beam splitter located at the beam path introduced portion of the heating beam to another photo-detector, extracting signal of the heating beam as a comparison with the probe signal.

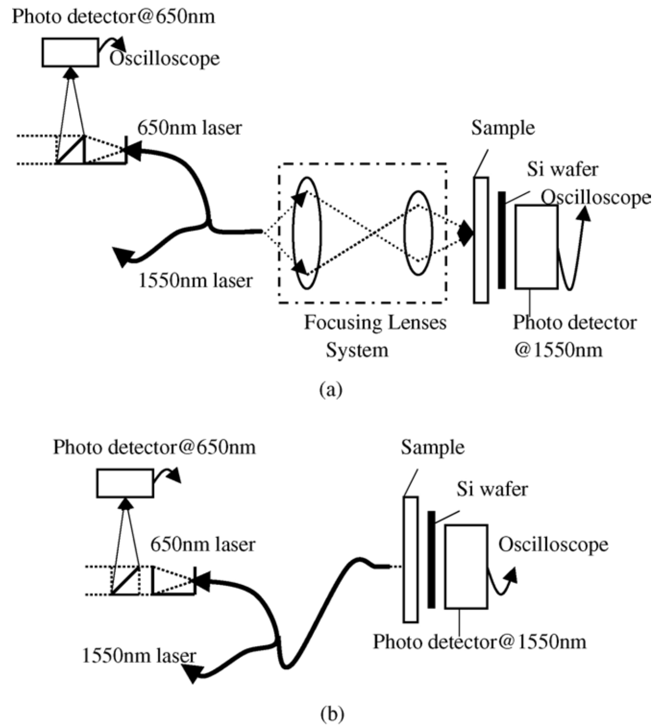

Fig. 1. (a) Apparatus of a VO_2 IR shutter system with a focusing system composed of convex lenses. (b) Apparatus of a VO_2 IR shutter system with a focusing fiber lens instead of convex lenses.

3. Results and discussion

The switching signal is associated with the relative position of the sample during measurement in the system shown in Fig. 1a. As shown in Fig. 2, under continuous square heating pulse of 1 kHz and 13 mW at different positions, the oscillation amplitude of the probe beams (P_{oa}) increases from position A to C, it is clear that the transmittance drops simultaneously as the heating process starts. The transmittance

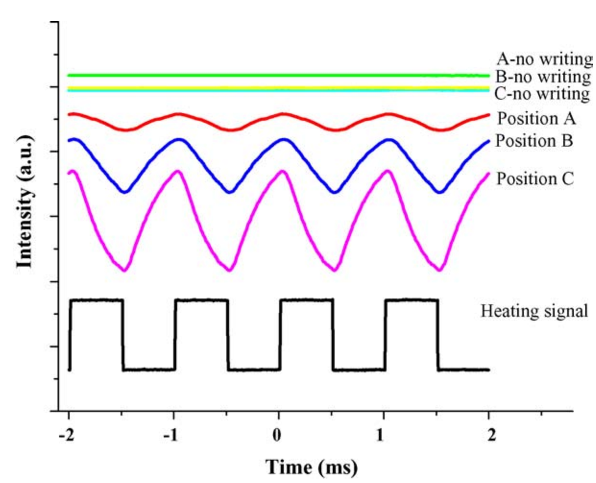

Fig. 2. The probe beams measured at different positions with/without a heating signal. Position C is where the oscillation amplitude is largest and position B locates between position A and C.

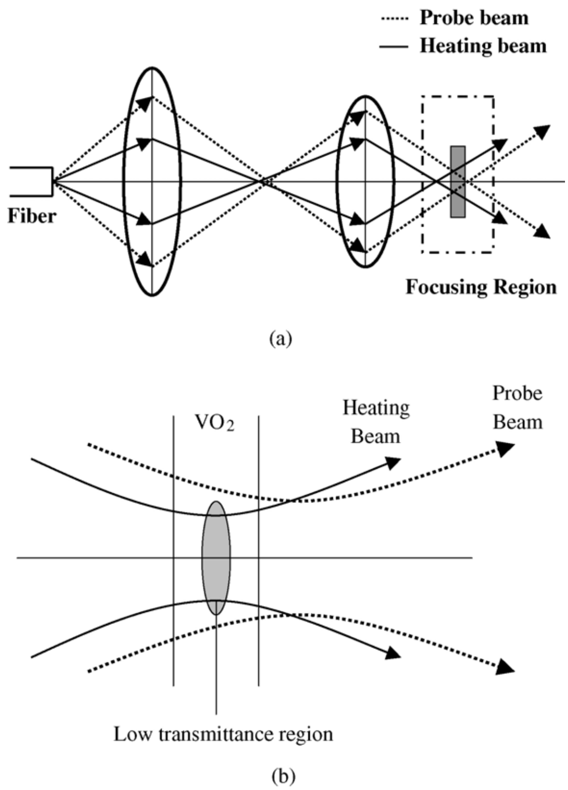

Fig. 3. (a) Optical traces of probe and heating beams in measurement system. (b) Relative positions of focal points of heating beam, probe beam and the low transmittance region.

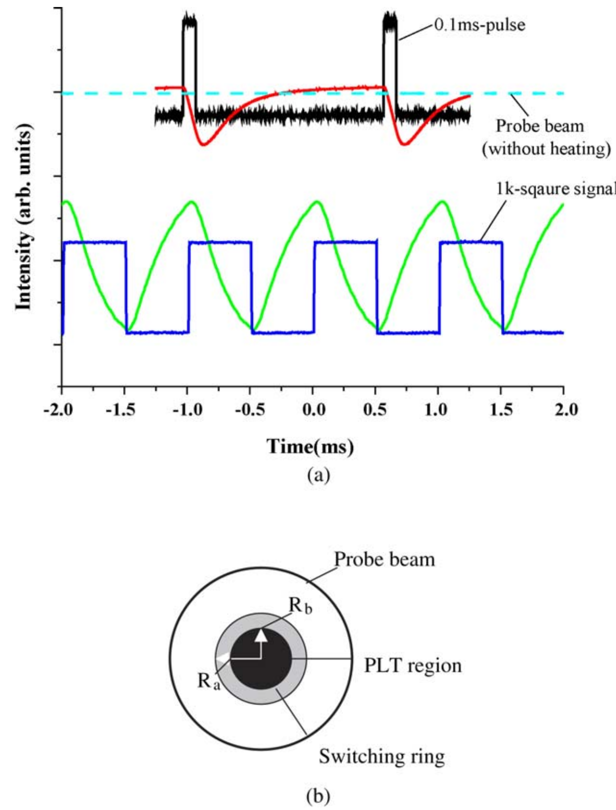

Fig. 4. (a) Comparisons between probe beams under square heating signal of 1 kHz, heating pulse of 0.1 ms and without a heating signal. (b) The relative areas and distribution of PLT region and switching ring within the probe beam.

returns to its original value as the heating stops. On the other hand, the average power level decreases as P_{oa} increases. But the average power levels of probe beams without heating differ greater from those under heating as the P_{oa} increases.

The mechanism of this optical shutter is the formation of low-transmittance region within the probe beam. As shown in Fig. 3a, both beams irradiate from the fiber end with different dispersive angles and pass through the lens system. Measurements by CCD demonstrate that the focal point of the probe beam locates behind that of heating beam because of the smaller refractive index of lenses at 1550 nm. The mismatch of focal points makes the projected area of probe beam on the sample always larger than that of phase change area, leading to a low-transmittance region within the probe beam, as shown in Fig. 3b. The comparison between different heating processes, as shown in Fig. 4a, shows that the P_{oa} induced by heating pulses of 0.1 ms with 1 ms period and 13 mW diminishes and the final power level returns to its original value. On the other hand, under continuous square heating pulse of 1 kHz and 13 mW, the highest power level of the probe beam is still lower than that without heating pulse, indicating the formation of permanent low-transmittance (PLT) region within probe region on the sample. As shown in Fig. 4b, once the PLT region forms, the switching of probe beam is caused by the transmittance change on the “switching ring” outside the PLT region. Once the writing pulse turns on, the radius of PLT region varies from R_a to R_b as time goes from T_a to T_b. R_b is the radius of PLT region because the transmittance is always kept low within the area during switching. The relationship between P_{oa} and radius of low-transmittance region can be expressed as

$$P_{oa} \propto \frac{\pi(R_a^2 - R_b^2)}{A_p} \quad (1)$$

where A_p is the area of probe beam on the sample. In the other words, P_{oa} is proportional to the area of switching ring. From Eq. (1), once A_p is fixed, larger power increases both the PLT and switching ring. As heating power increases shown in Fig. 5, the average power level of probe beam decreases but P_{oa} increases. That is because the increase of heating power from 12 to 17 mW results in larger PLT region and larger switching ring, which is approximately proportional to circumference of PLT region. On the other hand, longer cooling time can increase area of switching ring, furthermore, P_{oa}, so that higher frequency of continuous square heating pulse will produce lower P_{oa} because the difference in R_a and R_b is too small.

Due to the sensitivity limitation of IR photo-detector, the highest rate of detected continuous IR signal is 120 kHz in our system, as shown in Fig. 6. It is also demonstrated that a pulse of only 1 μs and 13 mW can be used to stimulate an IR pulse, as shown in Fig. 7. From Eq. (1), the numerator

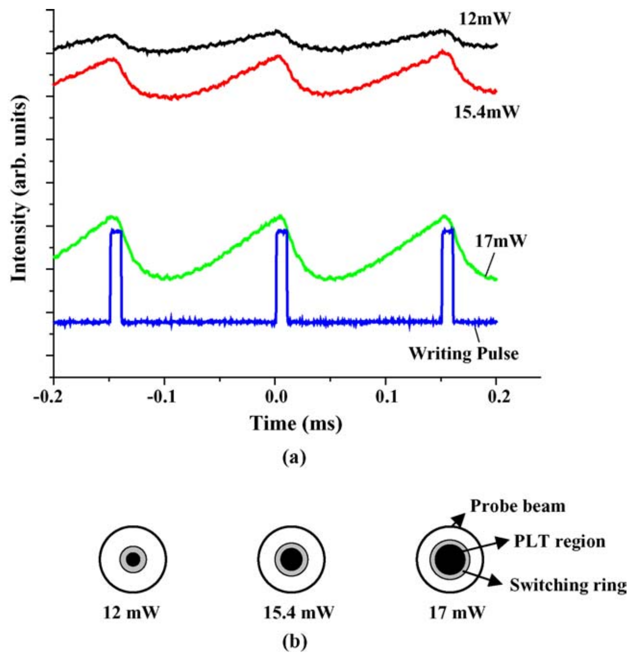

Fig. 5. (a) The switching reaction, comparisons of PLT regions and switching rings of VO_2 sample under 10 μs pulses of heating power 12, 15.4, and 17 mW, respectively. (b) Comparisons of PLT regions and switching rings under 10 μs pulses of heating power 12, 15.4, and 17 mW, respectively.

term is mainly limited by the structure of sample and heating signal. However, a enhancement of P_{oa} can also be achieved by the decrease of denominator, indicating that larger portion of probe energy is required to pass through the switching ring by decreasing the focal points of both beams, as shown in the comparison between Fig. 8a and b. Of course, once PLT region vanished to zero and the probe area is totally covered by the switching region, the VO_2 shutter can work under higher switching rate and lower power consumption.

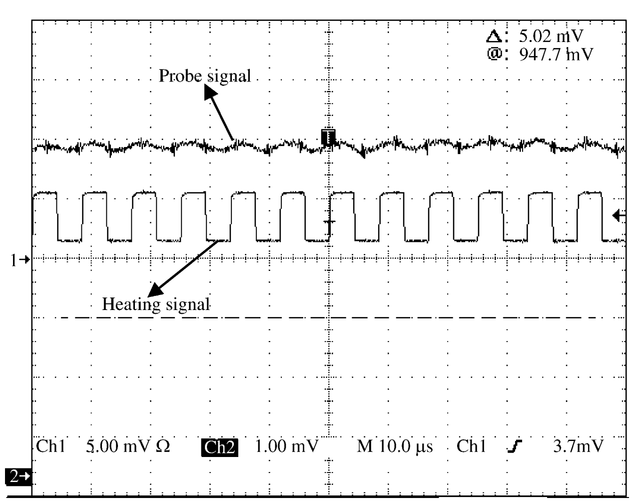

Fig. 6. Probe signal stimulated by a continuous heating signal of 120 kHz and 13 mW. (Focusing system composed of convex lenses.)

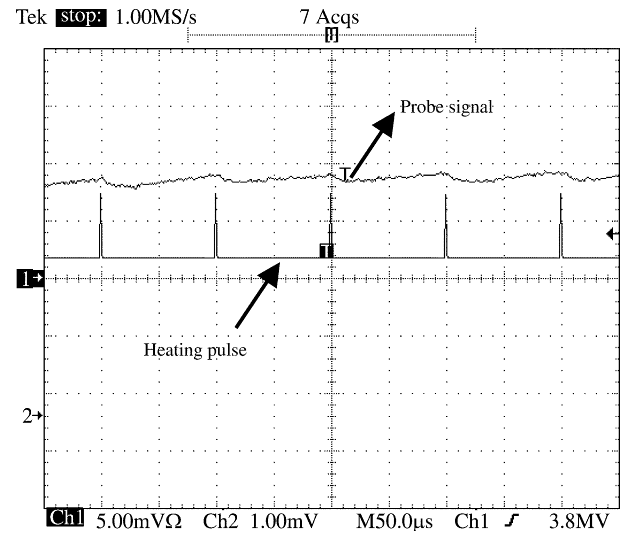

Fig. 7. Probe signal stimulated by a heating pulse of 1 μs and 13 mW. (Focusing system composed of convex lenses.)

The ways to decrease the focal point deviation of both beams are to reduce the quantities of focusing lenses and propagating distance of both beams in the free space. The fiber lens, often used in optical communication, is used here to focus both beams on the sample because it can simplify the focus system and reduce the focal point deviation of both beams. The second system, shown in Fig. 1b, is used to measure the optical responsibility of the same sample. The highest

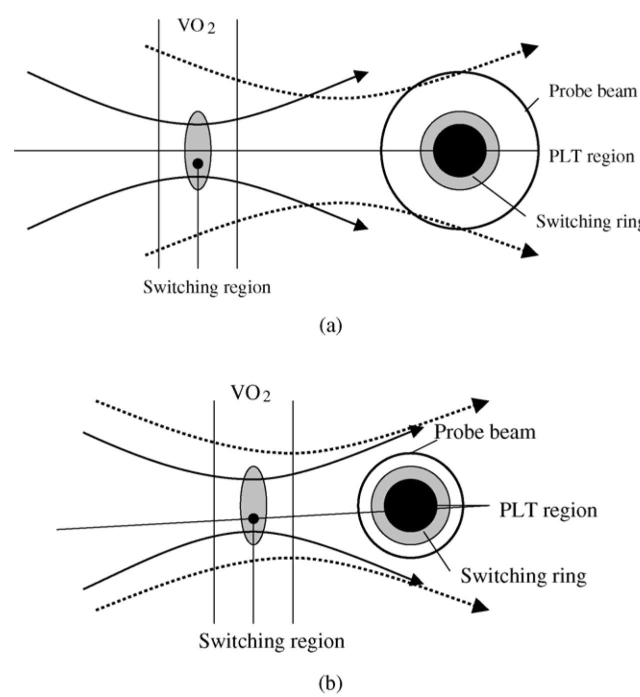

Fig. 8. (a) Area of probe beam and switching ring as the distance between focal points of the probe beam and heating beam is large. (b) Area of probe beam and switching ring as the distance between focal points of the probe beam and heating beam is smaller than that of (a).

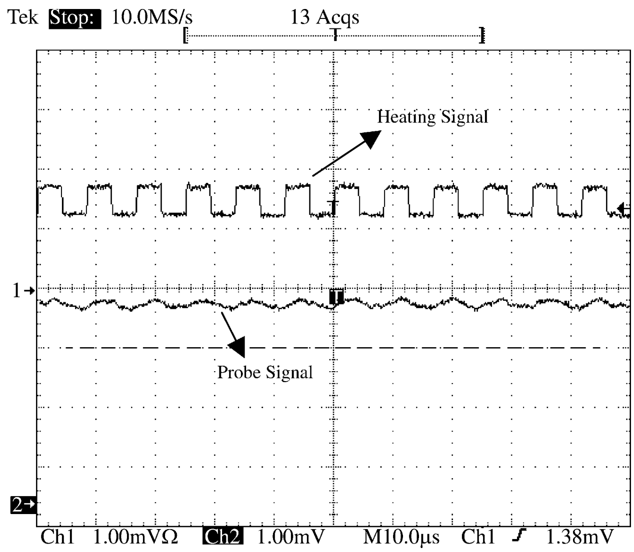

Fig. 9. Probe signal stimulated by a continuous heating signal of 120 kHz and 3 mW by using fiber lens.

rate of this system, as shown in Fig. 9a, is also 120 kHz but the heating power is only 3 mW, much lower than that in the previous system. As the heating power increases to 5 mW, no occurrence of switching indicates the PLT region that already covers the area of probe area. On the other hand, a pulse of only 70 ns and 13 mW can be used to trigger an IR pulse, as shown in Fig. 10, also implying that the switching area forms under low heating energy. The lowest pulse width to stimulate an IR pulse in the system is close to 35 ns indicated in Ref. [5]. Although the required pulse width to stimulate an IR pulse decreases to 70 ns, the same highest switching rate by continuous heating in these two systems is the same. This indicates that the balance between heating and cooling efficiency by modulation of device structure is the next important issue to remains to be solved for utilizing VO_2 as a higher speed IR shutter.

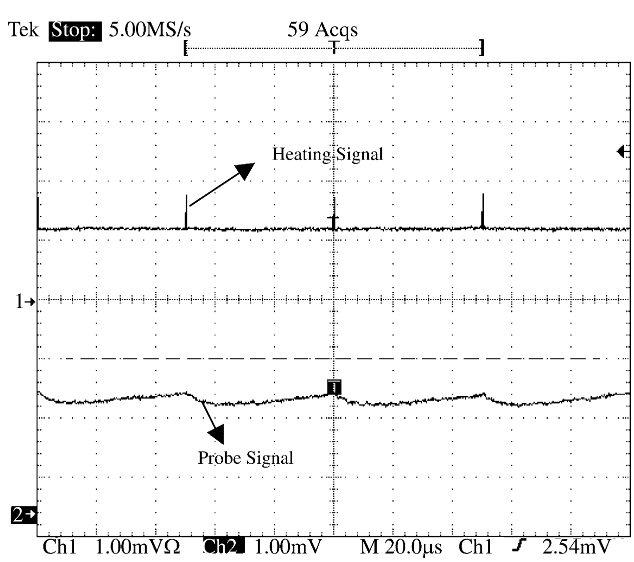

Fig. 10. Probe signal stimulated by heating pulses of 70 ns and 13 mW by using fiber lens.

4. Conclusion

A VO_2-based IR pulse generator has been demonstrated without precious alignment system for probe and heating beams. An optical system, integrated with WDM, either lenses system or fiber lens, and a sample of VO_2 film on glass substrate sandwiched by a Si film, is setup to utilize VO_2 as a practical IR shutter. A permanent low-transmittance region is formed within probe beam and the switching of probe beam is caused by formation of switching ring around PLT region. The highest rate of detectable continuous IR signal is 120 kHz synchronously with heating signal in system. A heating pulse of only 1 μs and 13 mW can stimulate an IR pulse. However, it requires only 3 mW to result in a continuous response to the probe beam of 120 kHz by using fiber lens instead of convex lenses. A heating pulse as short as only 70 ns and 13 mW can also stimulate an IR pulse by using fiber lens, implying that lower power consumption can be achieved by decreasing the deviation of focusing points between both beams. The limitation of switching rate under continuous heating pulse is owing to the low dissipation of accumulated heat, resulting in a small area of switching ring. In order to improve the switching rate of continuous IR signal, modification of device structure is the next important issue to be solved for utilizing VO_2 as the high speed IR shutter.

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