Nonlinear transmission through a tapered fiber in rubidium vapor

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Abstract: Sub-wavelength diameter tapered optical fibers surrounded by rubidium vapor can undergo a substantial decrease in transmission at high atomic densities due to the accumulation of rubidium atoms on the surface of the fiber. Here we demonstrate the ability to control these changes in transmission using light guided within the taper. We observe transmission through a tapered fiber that is a nonlinear function of the incident power. This effect can also allow a strong control beam to change the transmission of a weak probe beam.

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1. Introduction

Tapered optical fibers (TOFs) with diameters less than the wavelength of the guided light have been well characterized [1] and shown to have a wide range of applications including optical sensing [2], microtoroidal coupling [3] and various non-linear optical effects [4-6]. Because a portion of the power is guided in the evanescent field [7], TOFs experience significant changes in transmission when the silica-air boundary is contaminated. For this reason care is taken to isolate TOFs from dust and other contaminants.

In experiments that involve atomic media, the degradation of the surface of the fiber can be more difficult to prevent because atoms tend to accumulate. This is especially troublesome with rubidium and special techniques are often needed to prevent a loss in transmission. It has been suggested that coating the surface of the TOF with a substance such as organosilane [8] may prevent the degradation but has not yet been demonstrated on fiber devices of this type. Under appropriate conditions, sufficient heating of the taper may reduce the accumulation of rubidium [4]. In addition, there is evidence to suggest that the atoms could be desorbed using light-induced atomic desorption (LIAD), in which photons provide the energy required to remove the atoms from the surface. LIAD has been observed on various substrates coated with organic materials [9] and paraffin [10] as well as on uncoated surfaces [11].

In this work we demonstrate a new non-resonant effect in which atomic rubidium is removed from the surface of a TOF using low power light propagating through the fiber. This results in transmission through the TOF that is a nonlinear function of the incident power. The mechanism responsible for this effect is thought to be a combination of LIAD and possible heating of the tapered region. In either case, these effects represent a nonlinear relationship between the input and output powers of this system rather than a true nonlinear optical effect.

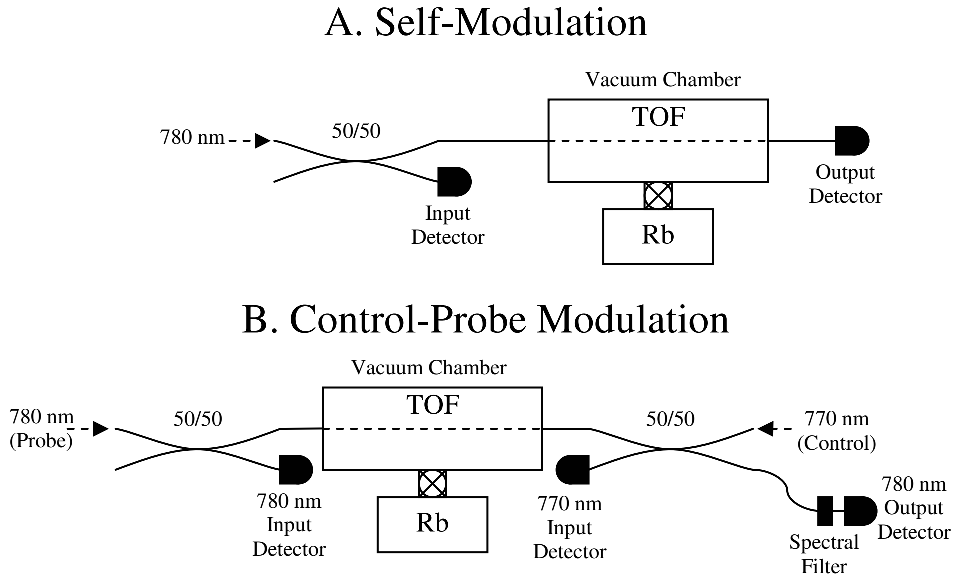

Fig. 1. The experimental setups used to investigate the nonlinear transmission through the TOF. (a) Self-modulation of transmission (b) Control-probe modulation of transmission

2. Experiment

The setups shown in Figure 1 were used to investigate the transmission through the TOF as a function of input power. The main component of both experiments was a TOF placed in a vacuum chamber. The TOF was fabricated on a stainless steel mount using the flame-brush technique [1] with an oxygen-butane flame. The TOF was secured to the mount with Viton® washers to allow the entire setup to be transferred into the vacuum chamber. The fiber pulling was performed with computer controlled micro-positioners while the transmission through the fiber was monitored to determine when the taper diameter was in the single-mode regime. The taper waist diameter was about 440 nm with a length of approximately 2 mm. The TOF was connected to optical fibers outside the vacuum chamber through custom-machined Teflon feedthroughs [12] and connected to standard fiber using gel-splices. The vacuum system was first baked for 24 hours at 160°C to reduce subsequent outgassing at lower temperatures. The background pressure after bake-out was typically 10^{-8} torr. A valve could then be opened to release rubidium into the chamber. During experiments the primary chamber was kept at 125°C and the rubidium source at 145°C.

A small radiative heating element consisting of a copper rod in contact with a black anodized aluminum radiating element was placed a few millimeters above the TOF in the vacuum chamber. This rod was heated to 155°C throughout the baking process and left at that temperature when the remainder of the system was cooled. This prevented the long-term accumulation of large amounts of rubidium on the taper, which would reduce the transmission to the point where it could not be recovered using our optical technique.

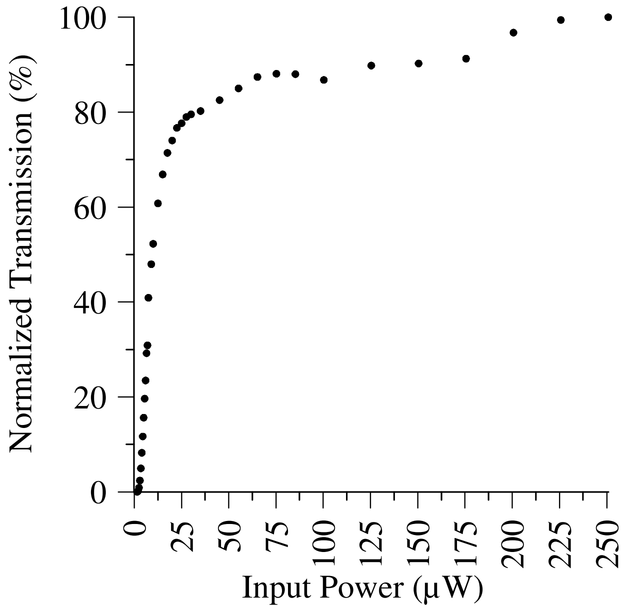

Fig. 2. A plot showing the increase in the percentage of light that is transmitted through a TOF as a function of the input power. Transmission is normalized to the maximum transmission at high power levels.

A. Self-modulation of transmission

A plot of the typical relation between input power and percent transmission is shown in Figure 2. This data was taken using the setup shown in Figure 1a with a probe frequency 100 GHz detuned from the D2 line of rubidium using a frequency-stabilized diode laser. The plot shows that at low input power the transmission through the TOF is negligible. As the power is increased there is a rapid increase in the percentage of transmitted light. The transmission then levels off and slowly approaches the transmission properties exhibited by the taper in the absence of rubidium vapor. Similar dependence on input power was observed at wavelengths throughout the range of our tunable laser (about 760-780 nm) as well as at lower wavelengths such as 650 nm.

The data shown in Figure 2 were taken with 15 seconds of settling time for each point. We observed a slow increase with the value of each point if settling times were longer, particularly at the higher range of the figure. As a result of this settling time the transmission exhibited hysteresis upon reduction of the input power.

B. Control of a weak probe beam

The ability of a guided beam to increase the transmission of the TOF allows the use of a strong control beam to modulate the transmission of a weak probe beam. To demonstrate this, we used the setup shown in figure 1b with a counter-propagating control beam at 770 nm and a weak (~ 1 μW) probe beam at 780 nm. The back-reflections from the control beam were then filtered out using a spectral filter and polarization analyzers as needed.

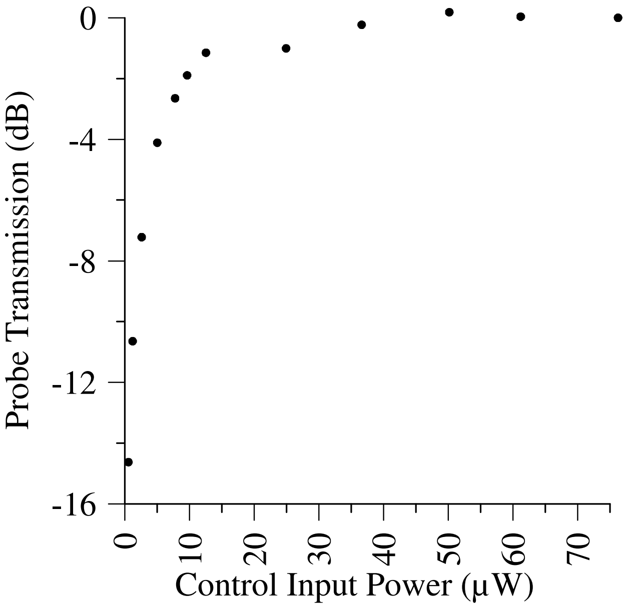

Fig. 3. A plot showing the increase in the transmission of a weak probe beam (~1μW; 780 nm) as a function of the input power of a stronger counter-propagating control beam (770 nm). Transmission is computed relative to the maximum probe power to show the dynamic range of the effect. The stronger beam has been removed using a tunable wavelength filter as shown in figure 1b and the input power of the probe beam remained constant.

Figure 3 shows that a control beam with power on the order of microwatts can be used to control the transmission of a counter-propagating probe beam of a different wavelength and much lower power. The control beam was able to modulate the probe beam by 16 dB. In principle, this result suggests that this effect could be used to construct an all-optical switch or modulator.

C. Atomic spectroscopy of the Rb D2 line

If an off-resonant control beam were to be employed to increase the transmission of a probe beam in experiments in which the probe interacts with an atomic medium, then the control beam should not significantly affect the atomic interactions. To test this, scans of the single-photon absorption around the well-known D2 line were compared under various conditions [4,13]. Figure 4 shows two plots without the control beam (770 nm) at two different probe (780 nm) power levels and similar plots with the control beam at a power large enough to dramatically enhance the transmission through the TOF.

The plots without the control beam (A and B) show that relatively large probe power levels are required to decrease the visibility of the resonance dips due to saturated absorption [14,15]. Plots C and D show similar saturation effects at much lower probe powers when a strong control beam is applied at 770 nm. This suggests that the layer of rubidium atoms on the surface of the tapered fiber greatly reduces the interaction of the probe beam with the atomic vapor. Application of a non-resonant control beam effectively desorbs the rubidium atoms and allows the probe beam to fully interact with the atomic vapor.

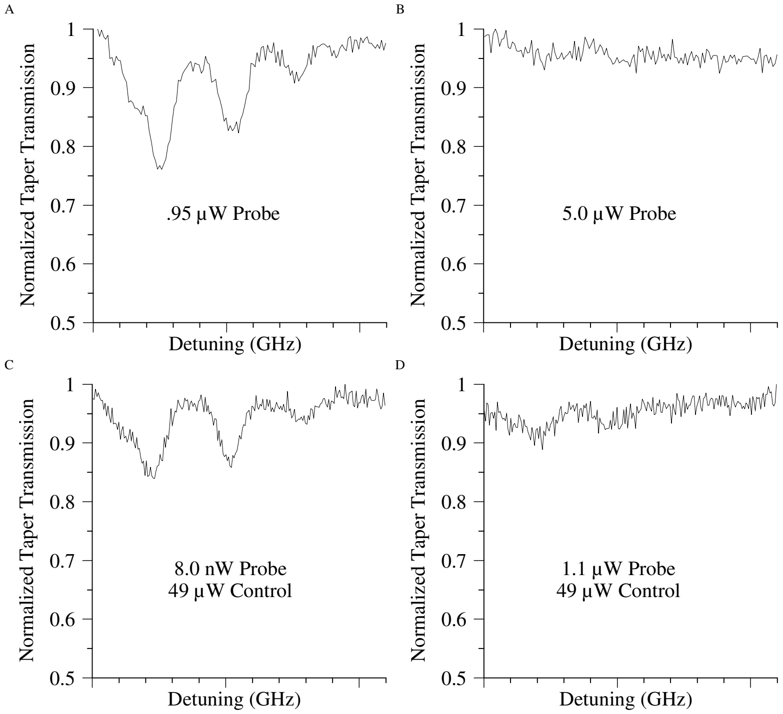

Fig. 4. Plots showing the 780 nm transmission through the TOF as a function of frequency detuning near the D2 line of natural rubidium. Each tick is one GHz and all plots shows the same range. (a) No control beam, .95 µW 780 nm (b) No control beam, 5.0 µW 780 nm (c) 49µW of 770 nm and 8.0 nW 780 nm (d) 49 µW of 770 nm and 1.1 µW of 780 nm.

3. CONCLUSIONS

All of the effects described above were greatly reduced when the rubidium oven was cooled back down to room temperature to reduce the rubidium density. This suggests that these effects are indeed due to rubidium on the surface of the tapered region.

We have shown that the transmission through a tapered optical fiber in rubidium vapor is a nonlinear function of input power. These effects can be used as an optical method to prevent the build-up of rubidium on TOFs. Control of a weak probe beam by a non-resonant control beam has also been demonstrated and may be of practical use as a switch or modulator. Preliminary tests of atomic spectroscopy in a TOF using this technique have been carried out.

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