All-optical switching based on inverse Raman scattering in liquid-core optical fibers

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We report on a new platform for all-optical switching based on inverse Raman scattering in liquids. Narrowband switching, which could be suitable for wavelength-division-multiplexed applications, is demonstrated using integrated liquid-core optical fiber infiltrated with both neat liquids (CCl_4 and CS_2) as well as an organic chromophore (β-carotene) dissolved in CCl_4. Compared to standard glass optical fibers, these liquids have much larger Raman loss coefficients, which help reduce the pump power by at least an order of magnitude. Further improvements can be expected with the development of highly soluble organic compounds possessing large Raman cross sections.

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All-optical switching is recognized to be important in future high-speed signal processing and telecommunication networks. Significant research effort has been devoted to the development of practical and robust all-optical switching schemes to significantly improve the current technology [1–4]. We have recently reported on the use of inverse Raman scattering (IRS) [5] as an effective mechanism for all-optical switching in a standard Ge-doped silica optical fiber [6]. This scheme has several significant advantages, including compatibility with current fiber optical networks and ultrafast operational speeds. However, due to the modest optical nonlinearity of standard glass fibers, the pump power requirements are still relatively high. Here we report on all-optical switching based on IRS in liquids, which have significantly larger macroscopic nonlinearities compared to glass, thus reducing the power requirements for all-optical switching based on IRS by at least an order of magnitude. Furthermore, Raman resonances in liquids are typically much narrower ($<10\ cm^{-1}$ FWHM) than in glasses, allowing us to target wavelength-division-multiplexing (WDM) applications. Recently, narrowband all-optical switching based on IRS in silicon ring resonators was theoretically investigated in [7]. While this is an intriguing platform for IRS-based switching, the issues associated with pump-induced carrier absorption typically encountered in silicon are easily avoided in the materials investigated here since multiphoton resonances are absent in the spectral ranges of interest.

Liquid-filled optical fibers are an attractive platform for various applications in nonlinear optics and sensing [8–14]. We have recently developed a new gap splicing technique that allows for preparation of integrated liquid-core optical fibers (i-LCOFs) [15]. This development has removed the main practical obstacle in utilizing liquids for various applications. It is now possible to work with liquid waveguides without the tedious handling and alignment procedures traditionally required.

We use fused silica capillaries with different inner tube diameters (10, 5, and 2 μm) purchased from Polymicro, Inc. in our experiments. The outer diameter is 125 μm, matching well with the standard single-mode fibers used here. The gap splices are performed using a Vytran Corp. FFS-2000 filament splicer. The detailed description of this splicing technique has been reported elsewhere [15].

We use a mixture of CCl_4 and CS_2 (3%–100% by volume depending on the diameter of the capillary) to fill the capillary of the i-LCOF. The choice of liquids is based on the two following requirements: (1) the index of the liquid must be slightly larger than that of fused silica for guiding via total internal reflection while still maintaining single-mode operation and (2) the liquid should be transparent in the spectral region of interest (near-IR in our case). As a rule of thumb, solvents with OH or CH bonds must be avoided since these compounds have strong vibrational overtone absorption bands in the near-IR. The filling was done by capillary action, so no special equipment was needed. The refractive index (at around 1550 nm) of CCl_4 is ~1.45, and that of CS_2 is ~1.59. The concentration of CS_2 is varied to create the target index contrast and consequently the appropriate NA of the fiber to ensure single-mode operation.

Loss-based switching via IRS was performed on CCl_4 in an i-LCOF. The entire waveguide geometry consists of ~1 m of SMF28 spliced to each end of a 1 m capillary with 10 μm inner diameter. We used a mixture of CCl_4 with 3% of CS_2 by volume to fill the core of the fiber. The total linear loss through the entire fiber system at around 1550 nm was less than 10%. The experimental setup is shown in Fig. 1 and is similar to that reported in [6]. The pump was a narrow linewidth pulsed (pulse duration ~3 ps) source at 1550 nm (50 MHz repetition rate). The synchronized anti-Stokes (probe) beam was a supercontinuum source with ~2 mW average power over the targeted spectral region [16]. Both the pump and anti-Stokes pulses are generated from a single mode-locked

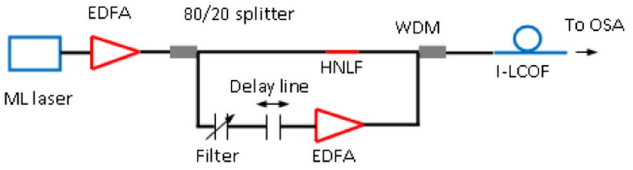

Fig. 1. (Color online) Schematic diagram of the experimental setup. EDFA, erbium-doped fiber amplifier; HNLF, highly nonlinear fiber; ML, mode locked; WDM, wavelength division multiplexer; OSA, optical spectrum analyzer.

Er^{3+}-doped fiber laser source using a carbon nanotube saturable absorber provided by Kphotonics, LLC. A WDM coupler (cutoff ~1500 nm) was used to combine the pump and anti-Stokes arms. A fiber-coupled delay line was used to overlap the pump and the anti-Stokes pulses in time. When this condition was met, we observed significant loss, which appeared as dips in the optical spectrum of the anti-Stokes beam (Fig. 2). The losses occurred at anti-Stokes wavelengths where known vibrational modes of CCl_4 exist, as expected. It can be challenging to measure the Raman spectrum of CCl_4 by traditional methods involving collection of scattered light since sensitive detection is required due to the low signal levels. Here we could measure the inverse Raman loss spectrum using a standard optical spectrum analyzer. The strongest observed optically induced loss was ~20 dB for the vibrational mode of CCl_4 at 460 cm^{-1}. We note that this induced loss is similar to that observed in a Ge-doped silica fiber [6] despite a reduced pump power, larger core diameter, and shorter fiber length employed here. These differences in modal intensity and path length are mostly compensated for by a marked increase in the Raman loss coefficient, the macroscopic parameter that controls the IRS response [17].

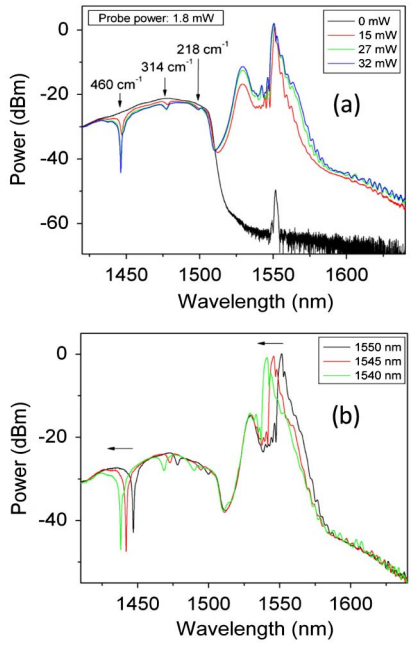

Fig. 2. (Color online) IRS switching using an i-LCOF filled with CCl_4. (a) Power dependence of the IRS response. (b) Loss spectrum tuned by changing the pump laser wavelength.

The bandwidth of the induced loss spectrum is quite narrow (~10 cm^{-1}) compared to the case where a standard Ge-doped fiber was used [6]. This should allow us to target a particular channel of a WDM network to be switched on or off while still maintaining a high operational speed (~100 GHz). To demonstrate this capability, we tuned the pump laser wavelength around the *C*-band and observed the corresponding shift of the IRS spectrum [Fig. 2(b)]. It is clear that the location of the loss bands has moved to maintain the same Raman frequency shift.

Next, IRS-based switching was also performed in a 0.6 m long i-LCOF with a 2 μm core diameter filled with 100% neat CS_2. Because of the mode mismatch between the i-LCOF and the standard coupling HI1060 fiber, the total transmission of the device was ~30%. Strong (~18 dB) optically induced loss corresponding to the Raman resonance of CS_2 at 667 cm^{-1} is clearly observed, as shown in Fig. 3. The power level required for this experiment is significantly reduced compared to the Ge-doped glass (~25 times) despite similar modal areas and a reduced path length for the CS_2-filled i-LCOF, the large Raman loss coefficient of CS_2 [17] being responsible for this marked improvement. We also observed significant spectral broadening of the pump and anti-Stokes pulses due to self-phase modulation at low power. This is a useful feature that can be exploited to generate broad supercontinuum using extremely low pump power.

While we have shown narrowband IRS switching with two neat liquids (CCl_4 and CS_2), further power reductions will likely require the use of molecules with very large Raman scattering cross sections (RSCs) as the IRS loss coefficient is proportional to the number density of molecules as well as their RSCs [17]. To this end, we chose to investigate β-carotene due to its large RSC [17,18], commercial availability, and good solubility in CCl_4. To demonstrate the feasibility of our platform for organic compounds, we prepared a solution of β-carotene (12 mM concentration) in CCl_4 with 5% CS_2 by volume and infiltrated it into a 0.5 m long i-LCOF with a 5 μm core diameter. The transmission loss through the entire fiber system was about 60%, worse than for CCl_4 alone, which could be due to overtone absorption from the solute. Similar IRS measurements were performed on the sample, and good signal loss was observed with 15 mW of pump power (see Fig. 4). To cover the entire spectral range (up to 1600 cm^{-1}), we had to scan the

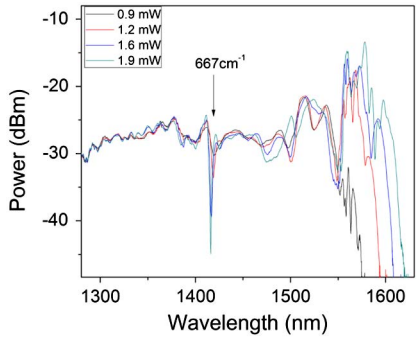

Fig. 3. (Color online) IRS switching using an i-LCOF filled with neat CS_2.

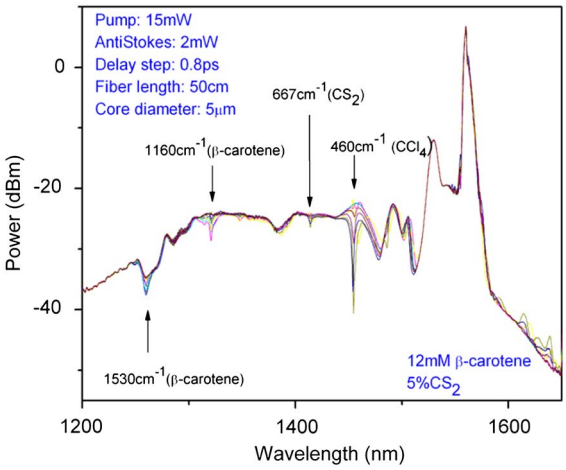

Fig. 4. (Color online) IRS switching using an i-LCOF filled with β-carotene dissolved in CCl_4 and 5% CS_2 by volume.

temporal delay between the pump and signal pulses at a step size of 0.8 ps to accommodate the longer (~8 ps) chirped probe beam. As shown in Fig. 4, the IRS signal from various components (CCl_4, CS_2, and β-carotene) of the solution can be identified in the anti-Stokes spectra.

It is worth noting that the optically induced loss due to the Raman vibrational mode of β-carotene at 1160 cm^{-1} is around 5 dB, which represents only a fourfold reduction in IRS signal compared to CCl_4. Since the optical geometries for both the β-carotene and CCl_4 measurements possess similar products of modal intensity and path length, the differences in signal strength can be mainly attributed to differences in the IRS loss coefficients. Interestingly, the β-carotene solution possesses a concentration that is nearly 1000 times less than that of the neat liquid, but the IRS coefficient is compensated by a nearly 1000 times increase in the RSC compared to CCl_4 [17]. Consequently, we would expect much better performance in terms of pump power reduction and signal loss contrast if molecules with similar or improved RSCs can be integrated at even higher concentrations.

In conclusion, we have developed a new platform for all-optical switching using neat organic liquids and solutions of molecules with large RSCs. This technology avoids the need for free-space coupling into the core of an i-LCOF, making it more attractive for practical applications. This approach has allowed for the demonstration of IRS-based all-optical switching with comparable signal contrast while utilizing over an order of magnitude smaller pump power compared with Ge-doped fiber.

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