PHYS 714 ARTICLE REVIEW

Ultrafast optical transistor and router of multi-order fluorescence and spontaneous parametric four-wave mixing in Pr^{3+}:YSO

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We review a recent article [*Opt. Lett* **40**(20), 4599 (2015)] detailing the capabilities of a new ultrafast optical transistor. We first provide some background information from cited references and other works necessary to understand the results presented. We then follow with a critical commentary of not only the results, but also the content and structure of the article, and conclude by comparing the results presented with those of other groups.

I. BACKGROUND INFORMATION

To remedy the weak introduction and nonexistent motivation, we go through the references provided by the authors to give some idea of the results on which this work builds upon. In the late 1990's, electromagnetic waves were used to induce transparency in certain materials, allowing them to absorb less light at certain wavelengths. This effect has now been called electromagnetically induced transparency (EIT). At first, microwaves were used to decrease the transparency of ruby by 20% at a specific wavelength in 1995 [1]. A couple of years later, radio-frequency fields were used to induce a transparency in an electron spin resonance transition in nitrogen-vacancy centers in diamond [2]. While seemingly unrelated to optical transistors, EIT has allowed for the storage of photons in these materials. In 2005, Longdell et al. [3] demonstrated the storage of light for longer than a second in a Pr_3^+:Y_2SiO_5 crystal using EIT thanks to the long coherence time of the crystal's hyperfine transition. Then in 2008, Beil et al. [4] used EIT to store and retrieve information, also encoded as nuclear spins in Pr^{3+}:Y_2SiO_5. To retrieve information, transparency is induced to ensure that absorption is no longer possible, then you simply wait for the photon encoding your information to be emitted and detected. Also in 2008, Wang et al. [5] were able to store information in Pr^{3+}:Y_2SiO_5 encoded as atomic spins, which they were then able to destroy or erase using photons with an 85% success rate. Fleischhauer et al. [6] published a review article on EIT in 2005 focusing on potential applications in nonlinear optics and quantum information. As expected, being able to store and retrieve photons using EIT paved the way for further applications which is where previous contributions by the authors begin to appear. In 2012, Li et al. [7] demonstrated all-optically controlled routing. They spatially split four-wave mixing beams and implemented a space demultiplexer and router via splitting one spot to multiple spots. This is not the routing mechanism implemented by the authors but is a previously realized alternative. In 2014, Zheng et al. [8] demonstrated the seeded spontaneous parametric four-wave mixing process associated with the fluoresence signals of Pr^{3+}:YSO and suggest the possibility of amplification processes using such a technique. While seemingly the most relevant reference because the authors use these signals in this work, it is not included in the introduction, but as a technical reference much later.

II. COMMENTARY

A. Experimental

The Pr^{3+}:Y_2SiO_5 (or Pr^{3+}:YSO) crystal is placed in a cryostat at 77 K. Three tunable dye lasers are used to generate the pumping fields $\mathbf{E}_i(\omega_i, \Delta_i)$, $i = a, b, c$ or $i = 1, 2, 3$, which excite and de-excite atoms in the crystal between energy levels $|0\rangle, |1\rangle, |2\rangle$, and $|3\rangle$. For some reason, the indices $i = a, b, c$ and $i = 1, 2, 3$ are used interchangeably without any pattern. There is no ambiguity so we feel the authors should have stuck to one set of indices. We shall mimic the author's use of them in this review. These four energy states form two three-level systems, a V-type ($|0\rangle \leftrightarrow |1\rangle \leftrightarrow |2\rangle$) and a Λ-type ($|0\rangle \leftrightarrow |1\rangle \leftrightarrow |3\rangle$) as shown in Fig. (1b) and (1c). The pumping fields $\mathbf{E}_i(\omega_i, \Delta_i)$ coming from the tunable dye lasers may be detuned away from any resonances with frequency detuning $\Delta_i = \Omega_{mn} - \omega_i$ where Ω_{mn} is the transition frequency between energy levels $|m\rangle$ and $|n\rangle$. So zero detuning, $\Delta_i = 0$, would be tuning exactly to the transition frequency, while red-detuning, $\Delta_i > 0$, would be tuning below the transition frequency and blue-detuning, $\Delta_i < 0$, would be tuning above the transition frequency. $\mathbf{E}_a$ drives the $|0\rangle \leftrightarrow |1\rangle$ transition, $\mathbf{E}_b$ drives the $|0\rangle \leftrightarrow |2\rangle$ transition, and $\mathbf{E}_c$ drives the $|1\rangle \leftrightarrow |3\rangle$ transition. Thus the V-type system uses $\mathbf{E}_a$ and $\mathbf{E}_b$, while the Λ-type system uses $\mathbf{E}_a$ and $\mathbf{E}_c$. The $\mathbf{E}_b$ and $\mathbf{E}_c$ fields counter-propagate with $\mathbf{E}_a$ as shown in Fig. (1a), possibly to allow for easy separation of the two beams [3], but no reason is given. A photomultiplier tube is used to detect fluoresence (FL) signals from the crystal. The Stokes and anti-Stokes signals from the four-wave mixing processes are detected by photomultiplier tubes with a fast gated integrator. The fast gated integrator or fast boxcar averager is used to improve the signal-to-noise ratio.

B. Control of FL and SP-FWM

The authors begin the discussion of their results by detailing how they control the fluorescence (FL) and spontaneous parametric four-wave mixing (SP-FWM) processes along with their observations of the output signals. The FL signal is used for switching purposes, while the SP-FWM signal is used for amplification.

A main result is the Autler-Townes (AT) splitting of the FL signal in the frequency domain [Figs. (2a6) and (2a7)] once the pump power $\mathbf{P}_a$ approaches 10 mW, causing an EIT in the crystal which may be used to realize the nonlinear switching behavior of a transistor. Of note is that this is only a partial transparency with the intensity dipping below the spontaneous emission baseline (blue dashed line). It is unclear whether a full transparency ($I = 0$) is desired or if simply having the intensity go below baseline is enough to implement a switching functionality. We assume that the difference between the peak and dip positions is what matters, i.e. the later defined switching contrast, however no comments are made suggesting the sort of fluorescence lineshape desired. A source of frustration is that one of the most important curves in the article, Fig. (2a7), which is meant to clearly show the AT splitting, is the only curve throughout the whole article plotted in yellow, allowing it to blend in with the white background and thus obscuring the data. We are forced to conclude that the authors have decided to intentionally obscure this crucial curve, possibly to avoid questions that may be brought up by reviewers that wish to more closely inspect it.

It seems that adjusting the pump power $\mathbf{P}_a$ provides both the required switching and amplification processes, while adjusting the frequency detunings may only provide one at a time. Zero detuning provides an AT split fluorescence lineshape required for switching, but blue-detuning is required for amplification of the SP-FWM signal. At best, the switching provided by zero detuning is of inferior quality [Figs. (2c6) and (2c7)] compared to that provided by adjusting the pump power [Figs. (2a6) and (2a7)] due to the slightly asymmetric lineshape and the dips remaining above baseline which would result in a lower switching contrast. Interestingly, the switching and amplification processes discussed later rely on changes in the pump power $\mathbf{P}_a$ and $\mathbf{E}_a$ polarization angle, not on the frequency detunings which isn't mentioned again. A common theme of this article seems to be that zero motivation is provided by the authors for the results presented. We do not see the frequency detuning mentioned again, except briefly in theoretical discussions, and so we are not sure why the effects of detuning are being discussed and presented. They have already been presented and discussed in previous works [6, 8, 9].

With the phase matching condition $\mathbf{E}_s = 2\mathbf{E}_1 - \mathbf{E}_{as}$, degenerate four-wave mixing can be observed in the form of Stokes and anti-Stokes signals. The authors only report the Stokes signal, and it is left unclear why the anti-Stokes is not reported. We assume the anti-Stokes signal is useless for the purposes of this work, but would it have killed the authors to use a few words to explain this. Another main result is that increasing the pump power $\mathbf{P}_a$ (or detuning) amplifies the output Stokes SP-FWM signal. While not particular to this figure only, the curves showing this amplification in Figs. (2b1)-(2b7) have all been trimmed to show the signal lineshape near the peak, leaving the reader to wonder what it looks like away from the peak and if that would have any effects on the amplification or switching.

Adjusting the $\mathbf{E}_a$ polarization may also be done to achieve AT splitting or amplification of the SP-FWM signal. It seems to result in the widest splitting accompanied by good amplification, almost on par with blue-detuning Δ_1, making it the best candidate for controlling amplification. Indeed, the optical amplifier is realized later on by adjusting the $\mathbf{E}_a$ polarization.

The authors also provide the FL and SP-FWM signals in the time domain along with comparisons to theoretical predictions in Fig. 3. Theoretical predictions for all curves in Fig. (3e) are given which all agree quite well, however only three of six curves are compared with theory in Fig. (3b). It is obvious that they agree well qualitatively however the predicted peaks are narrower (more pointed) and seem more asymmetric. With the other predictions missing, perhaps the density matrix elements given by the perturbation chain fail to describe the other three curves.

C. Optical switch

The all-optical switch, analogous to a conventional BJT operating in saturation mode as shown in Fig. (1d) is realized through the use of the fluorescence (FL) signal. The FL signal is used as the input signal while the $\mathbf{E}_a$ field acts as a control signal, analogous to the base current of a BJT or the gate voltage of a MOSFET. They operate the switch as if it were a PNP transistor. In the time domain, They define the ON-state of the switch by the condition $I > 0.2$ where I is the intensity of the input FL signal, and thus $I \leq 0.2$ defines the OFF-state. In the frequency domain, I being higher than the baseline defines the ON-state, while I being below the baseline defines the OFF-state. Switching contrasts of $C = 80\%$ and $C = 82\%$ are achieved in the time and frequency domain respectively. The higher the contrast ratio, the more well-defined or separated the ON and OFF-states are, as any overlap of the two states would obviously destroy the switching functionality. No discussion is provided placing this value in context, so the reader is left unsure whether 80% is acceptable or excellent. Surely the authors would not miss the opportunity to claim it as an excellent value if it were, so it is probably safe to assume that 80% is nothing extraordinary. No comparisons are made either, so the reader is again left unsure of the significance of this value relative to other works. Other definitions for the ON and OFF-states are used by other works [10, 11] so it is unclear why this definition is used by the authors. Without any motivation for this specific definition, the reader is led to conclude that the authors picked the definition that resulted in the highest switching contrast.

They report ON and OFF switching times of 5 ns along with rise and fall times of 10 ns. These times are limited by the electro-optical modulator which has a speed of 10 ns and the atomic coherence time which cannot be made any faster than nanoseconds due to the electro-optical modulator's speed. They claim that the total switching speed of 15 ns is a quadrature sum of several independent contributions, with no mention of what these contributions may be.

Another criticism of the curves plotted that is not particular to any single plot is that the dashed lines in Figs. (4b) and (4d) trace the positions of the baseline and peak but with only 2-3 data points, it is hard to believe that the dashed curve constitutes a trend. The dashed curves, while possibly obvious in their purpose, are never explained and no information is given on how they were constructed, again leaving the reader to conclude that the authors must have chosen the best trend to illustrate their desired results. However, the authors cannot necessarily be faulted for this as the misuse of statistics is rampant in science and this is merely an innocent example.

D. Optical router

The all-optical router is realized by controlling the dressing laser field $\mathbf{E}_a$. Increasing the pump power $\mathbf{P}_a$ to 5 mW causes AT splitting in the FL lineshape, resulting in routing by frequency-division multiplexing (FDM) which the authors call frequency domain multiplexing for some reason. The dip due to EIT does not go to zero so there is still a good fraction of the incoming light at the original frequency (about 50%) so perhaps it would be more accurate to call this a partial router. All previous results were reported to be optimal near $\mathbf{P}_a = 10$ mW however in this case they stop at 5 mW yet continue their dashed red trend downwards. It would be interesting to know what happens once the power is increased, although we suspect the obvious; that the process breaks down or fails, otherwise the authors would have reported on it.

Parameters are defined and calculated for their optical router such as the channel equalization ratio P and contrast index η. The authors give ranges for P and η, $80 - 90\%$ and $70 - 80\%$ respectively, and a short blurb describing the advantages of having both parameters be close to 100%. However, we feel this leaves the reader more confused than impressed. It may be the case that practical transistors require these parameters to be higher than 95%, or maybe 60% is good enough. If the authors have decided to describe and hide behind an arbitrary set of parameters with no interpretation or context, then perhaps the router is not a very good one as we have suggested previously.

E. Optical amplifier

The all-optical amplifier, analogous to a conventional BJT operating in active mode as shown in Fig. (1e), is realized through the use of SP-FWM. Fig. 5 details the results of operation as an all-optical amplifier. The SP-FWM signal is used as the input signal to be amplified while the $\mathbf{E}_a$ field is used a control signal to control the amount of amplification, from none to some maximum amount. Blocking $\mathbf{E}_a$ or keeping its polarization vertical corresponds to no amplification, while a horizontal polarization corresponds to maximum amplification. The maximum amplification or gain achieved was $G = 5.9$ for a V-type system. The output signal is theoretically modeled as $a_{\text{out}} = G a_{\text{SP-FWM}} N$ where N is the internal noise of the transistor. It's clear from Fig. (5a1) and (5c3) that amplification cannot be turned all the way down to zero, but at least it is barely above noise, which is nice.

It seems that the V-type system produces a larger gain, but no suggestions were given as to why. In general, the expected differences between the V-type and Λ-type systems were never discussed, so the reader is left to assume that they are being compared for purely investigative reasons and the V-type system seems to be the winner by far.

What is interesting is the omission of output signals for polarizations of $0° - 45°$ in the case of a V-type system, when they were included for the Λ-type system. We can only infer the possibility that the amplification process breaks down for polarizations below 45° for a V-type system and that the authors did not wish to disclose such results. We have no idea why they would be omitted otherwise, as the results should be roughly symmetric as in the case of a Λ-type system. It seems that they call 45° "vertical polarization "and simply refer to 90° polarization as "90°". We found this rather confusing as vertical should be given either as 0° or 90°.

F. Other works

Multiple attempts at realizing implementations of an all-optical transistor have been made using other methods, some quite exciting and high-profile and all of them much better communicated than the current work. We will cover some of them here to place the current work in the context of other attempts. In general, this work seems to describe the first experimental realization of an optical transistor using EIT in a nonlinear crystal with the FL and SP-FWM signals acting as the outputs, but not the first realization of an optical transistor using EIT. Other implementations seem to hold more promise mainly due to the possibility of extending and improving their work as their respective authors suggest. Once again, the authors of the current work provide no suggestions as to how their work may be extended to realize a practical optical transistor and so the reader is left to assume that the authors have hit a dead-end.

In 2012, Volz et al. [10] demonstrated the first ultrafast all-optical single-photon switch using pulsed two-color spectroscopy and polariton transitions to scatter photons in a strongly-coupled quantum dot-cavity system. They achieved a switching time of 50 ps due to their use of ultrashort 33-86 ps laser pulses, almost 3 orders of magnitudes faster than the 15 ns reported in the current work. While their single-photon switch may only be a switch, claiming that 15 ns is "ultrafast" may be a stretch, especially when MOSFET switching times are well into the sub-picosecond regime. In 2013, Chen et al. [11] demonstrated an all-optical switch and transistor gated by a single-photon based on EIT in a four-level Y-type system. Their single-photon optical transistors only has a gain of approximately $G = 2.2$, which is at least above unity opening up the possibility of all-optical quantum circuits with feedback and gain. Single-photon control seems to be somewhat of a holy grail for optical transistors, one which the current work cannot achieve due to the high pumping power ($\mathbf{P}_a = 10$ mW) required for AT splitting. In 2009, Hwang et al. [12] demonstrated that a single dye molecule can operate as an optical transistor and coherently attenuate or amplify a tightly focused laser beam, resulting in changes in transmission by up to -6% or $+0.5\%$ in a laser beam containing 10^6 photons/s. While not very much, this is already extraordinary work for a single molecule and they suggest that coupling the molecule to a nano-antenna could enhance the emission rate. A few months before publication of the current work, Kinsey et al. [13] demonstrated ultrafast carrier dynamics (< 1 ps excitation and recombination times) in Al-doped ZnO thin films. This provides a promising candidate for dynamic photonic devices including all-optical transistors. Multiple other implementations of all-optical switches and transistors have been experimentally realized using EIT [14], atomic rubidium vapor [15, 16], exitons [17], polaritons [18], semiconductor nanowries [19], and interstate Rydberg interactions in ultracold gases [20, 21].

Besides experimental demonstrations of optical switches and transistors, there have been multiple propositions and schemes for building all-optical transistors. In 2013, Neumeier et al. [22] proposed a circuit quantum electrodynamical setup for a single-photon transistor using photons propagating in two open transmission lines that are then coupled via two interacting transmon qubits, allowing for the control of one line using another. In 2009, Nazararthy et al. [23] proposed an all-optical logic architecture which would implement (N)AND, (N)OR, and X(N)OR logic gates. Furthermore, single gate structures may be used to implement multiple logic gates, much like how a conventional digital NOR gate may be used to implement any other logic gate. They also suggest an implementation for a phase-erasure or phase-reset function. Multiple theoretical schemes have been proposed for possible implementations of all-optical transistors using micro-resonators [24, 25], cross-phase modulation [26], and doped one-dimensional photonic-crystal cavities [27]. While these theoretical schemes are all exciting, we shall remain skeptical yet cautiously optimistic that they may one day result in successful implementations. There have also been criteria set forward for practical optical transistors by Miller [28] which we would have used to judge the current work, however almost all implementations satisfy no more than a couple of criteria at a time and six were put forward.

G. Language and structure

The English is unfortunately ridden with elementary grammar mistakes and awkward wording, which is fine however because it doesn't detract from the description of the results forming the meat of the article. However, all the authors do is describe the results, and very little interpretation is given beyond the comparison to a conventional BJT, which the authors kept hammering upon the reader. Absolutely no conclusion is provided, and the introduction is extremely weak, not providing any motivation for the work that was done. No attempt is made to compare the work to that of others either. Futhermore, the English is cumbersome to read and overly verbose at times. While we understand the journal has a strict page limit, the authors hit the 4 page limit without actually providing 4 pages worth of content. Had the authors spent less time rehashing the content of the captions in the text and explaining basic plots, they would have had some space to place an actual conclusion and a more substantial introduction that actually motivates the work discussed. The reference section seems to suffer somewhat as well, there are 12 references in the introduction and 1 in the body, and none of them ever repeat. This either is a clear showing of either laziness on part of the authors or their ultimate focus on strict page limits. If they could not clearly communicate their results in 4 pages, then perhaps the authors should have sought a journal that permits longer articles, such as Optics Express, which would have had even cheaper publication charges for an article of six pages or less. Perhaps it should have been the job of the reviewer or the editor to suggest this. Faults can even be found in the references themselves; reference number [3] in the article cites a completely irrelevant article about organic solar cells with a completely different author list, and reference number [10] in the article has the incorrect author list, an impressive feat considering the authors are citing another article by their own laboratory. We suspect the authors simply suggested three good friends as potential reviewers for their paper who provided lenient reviews, which would explain how this got past the peer review process as the editor probably has very little time to closely examine each submission. Scientific progress may be based on results produced on the scientific method, but effectively communicating scientific result should hold an equally important role. Readers and potential collaborators may decide to ignore works that have been poorly communicated.

III. CONCLUSION

While the work presented was interesting and worthy of publication, the overly descriptive language as well as the lack of interpretation and actual discussion throughout the article soured the excitement behind the results, turning into frustration as we shifted our attention from the abstract to the first paragraph. This frustration obviously manifested as bitterness in this article review, which has focused on the negative aspects for emotional reasons. While hugely inappropriate for a review of a scientific article, we feel our criticisms are well-founded and we have suggested many ways in which the article may be improved, resulting in bitter yet constructive criticism.

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