All-Optical Atomic Simulator on a Nonlinear Photonic Chip

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Here we demonstrate a number of new photonic devices inspired by the analogy with the atoms [1]. For example, we show how an all-optical analog of EIT in the system of two evanescently coupled waveguides can be used as an ultrafast broadband all-optical switch or on-chip quantum memory. Similarly, a STIRAP optical analogy gives rise to robust, noiseless frequency transduction when direct frequency conversion is impractical. Key advantages of nonlinear coupling between modes over linear coupling are: (1) the coupling strength can be changed by the end-user simply by adjusting the pump power, (2) the coupled modes may have the same or different frequencies, and (3) a synthetic spectral dimension can be added to the spatial dimension of a waveguide array.

Our numerical simulations show that a proper choice of the coupling constants suppresses the light transfer between the waveguides due to the EIT-like destructive interference. The results of numerical simulations are shown in Fig. 1, where the nonlinear coupling strength 0.23 mm^{-1} corresponds to a modest pump power of $\approx$ 200 mW and the frequency conversion normalized efficiency η = 2600% W^{-1} cm^{-2}, values reported experimentally for nanophotonic PPLN waveguides. The unique property of this effect is that both the input and the output remain at the same frequency, while the control field can be significantly detuned to eliminate Raman noise in $LiNbO_3$ [2]. This system can be used in practice as an ultrafast all-optical switch for faint states of light. Its switching time is limited only by the bandwidth of the TWM process in the nonlinear waveguide and thus can achieve sub-ps switching times.

Another well-known effect in atomic optics is STIRAP. In STIRAP, the population is transferred between two atomic states via two sequential coherent pulses. Here we propose using the all-

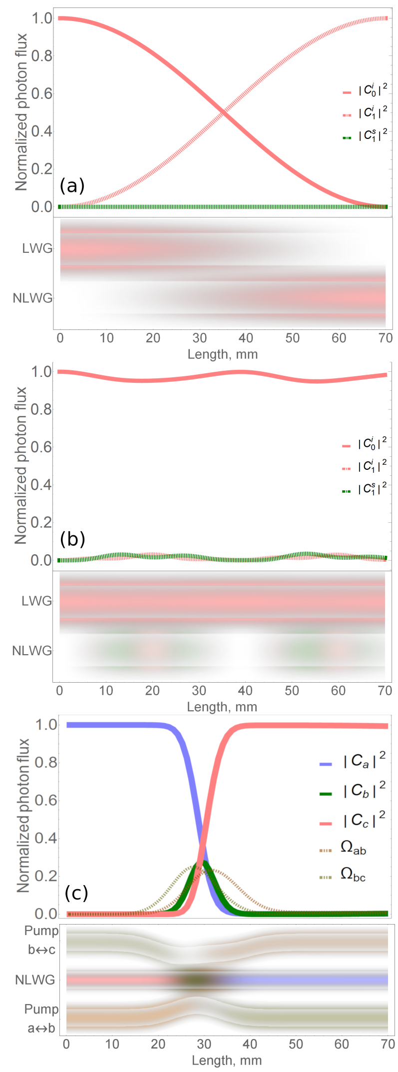

Figure 1: A numerical simulation of photon flux in nonlinear waveguides. (a,b) Ultrafast all-optical switch between a coupled linear waveguide (LWG) and nonlinear waveguide (NLWG) In the absence of an optical control pump field, the signal field is transferred from LWG to NLWG, (a). When the control field is applied, the signal field remains in LWG due to an EIT-like destructive interference (b). (c) All-optical STIRAP frequency conversion implemented with 3 coupled waveguides. Bottom figures show a conceptual layout of waveguides for the proposed experiment (not to scale); color gradients – the evolution of the propagating light fields

optical STIRAP for frequency conversion between the states that are hard to couple in a single-step TWM transduction. Numerical simulation and schematic waveguide design is shown in Fig. 1 (c). This design is particularly useful for noiseless transduction, where one-step transduction is either impractical (due to Raman noise and/or spontaneous down-conversion noise) or impossible (due to a transparency window). For instance, direct transduction between the two communication bands at 1310 and 1550 nm *via* TWM requires a pump at 8.5 μm, where most TWM crystals are not transparent. If transduction between the Rubidium D2 line at 780 nm and a telecommunication band at 1550 nm is desired, direct transduction would require a pump at 1570 nm, which will generate a substantial Raman background. Our STIRAP-inspired transducer offers a workable, noiseless alternative.

In this work, we introduced a theoretical formalism in which spatial and spectral modes of classical or quantum single-photon fields are mapped into energy levels of a fictitious atomic system interacting with external optical fields. This formal similarity between all-optical systems and atomic systems enables new interesting applications and all-optical simulations of atoms. To illustrate the potential of our theoretical framework, we presented two practical photonic applications based on traditional atomic phenomena: EIT and STIRAP.

References

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