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Review

High speed parametric processing controlled by few photons

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Abstract

Optical signal processing has long been recognized as a promising route to a new class of fast and energy efficient devices. The former parameter, the speed, has indeed been addressed in a number of different signal processing roles, confirming the superiority of optical signal processing devices with respect to their electronic counterpart. After gaining some maturity, the field has now advanced to reducing the energy consumption. In this regard, new efforts are directed toward designing an efficient photon interaction mediator, expected to provide both fast and energy efficient devices. The key topic of this review is the progress in longitudinal silica fiber dispersion engineering enabling efficient, non-reciprocal parametric mixers. We present how longitudinal dispersion fluctuations, once considered detrimental, can now be exploited to alter the phase matching condition, and thus, enable fast control of a high power beam by few photons. The potential of such a functionality in high-speed optical signal processing and sensing is discussed.

Keywords: Optical amplifiers; Nonlinear fiber optics; Nonlinear wave-mixing; Optical signal processing

Contents

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1. Introduction

Rapid transitioning of nearly all aspects of commercial and defense applications onto digital, distributed platforms have led to bandwidth demand, rising at a rate of nearly 60% per year [1,2]. Arguably, recent advances in optical transmission technology have enabled a capacity improvement, scaling with network traffic growth. However, the new optical network does not provide the functionality required by rapidly growing traffic: signal detection and processing is still performed by a bandwidth-limited electronic backplane. Worse, even if one is willing to match the bandwidth increase by brute scaling of the electronic plane, this strategy would lead to an unsustainable energy dissipation path [3]. These trends have motivated the pursuit of a new platform, capable of mediating efficient photon–photon interaction, in hopes to potentially lead to a new class of energy-efficient and fast, all-optical signal processing devices. Similarly, with a rising number of users requiring secure communication, an interest in direct-photon information processing and communication has increased, since it guarantees a qualitatively higher level of communication security [4,5]. This, in turn, motivates recent efforts in quantum signal processing and few-photon detection.

To meet this technological challenge, an all-optical signal processing device must simultaneously combine high nonlinearity, transparency, energy efficiency and be much faster than its electronic counterpart. However, basic optical properties of known materials prohibit the simultaneous realization of these requirements [6,7]. Therefore, different methods are often exploited to circumvent fundamental limits associated with each platform: an enhanced nonlinear response is achieved in resonant structures [8] or waveguides with long interaction lengths [9]. Although resonant structures can increase interaction efficiency, they also impose a strict limit on the response time, thereby restricting the achievable operational speed. In contrast, devices relying on a long interaction length have no such limits, but are constrained to pipelined signal processing. Although these types of devices are often associated with bulky physical platforms, recent demonstrations point to efficient interaction in millimeter-scale constructs [10], indicating that fast time response and long interaction length are not exclusive properties.

A mature fabrication process, large physical bandwidth and high nonlinear figure of merit in a highly nonlinear silica fiber (HNLF), has been a major drive in its deployment in applications such as parametric amplification [11], frequency conversion [11], supercontinuum generation [12], comb [13], sampling [14] and optical switching [9,15]. This paper reviews new design methods relying on these unique properties, recent feasibility demonstrations and future prospects of silica fiber-based devices controlled by few photons. The paper is structured as follows: The present section is devoted to recent trends and challenges in optical networks and the requirements for optical signal processing devices. In Section 2, the concept of a linear, single-pump, frequency-nondegenerate parametric mixer is introduced and the optimum fiber dispersion, maximizing the energy exchange, is identified. Section 3 is dedicated to the study