Metamaterials for classical and quantum data processing in all-optical fiber information networks

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***Abstract* – We report on the use of fiber-integrated plasmonic metamaterial absorbers in signal processing applications in coherent information networks. Quantum states filtering, perfect nonlinear absorption, all-optical gating and encrypted signal distribution are demonstrated.**

I. INTRODUCTION

Light manipulation in the optical fiber environment is a challenging but promising approach for all-optical information processing. In systems operating with classical signals, in-fiber data processing allows to overcome speed and energy limitations arising from conversion between optical and electrical signals in established solutions. In systems operating with quantum signals, in-fiber light manipulation is a base for scalable and robust quantum communication.

Metamaterials with on-demand parameters provide new tools for coherent all-optical signal processing. A striking example is control of light with light based on coherent perfect absorption, demonstrated recently with ultrathin plasmonic metamaterials both in the classical [1] and quantum [2] regimes in free space. Here we bring this technology in the fiber environment by designing and manufacturing fully-fiberized plasmonic metamaterials and integrating them in fiber networks for classical and quantum optical signal processing.

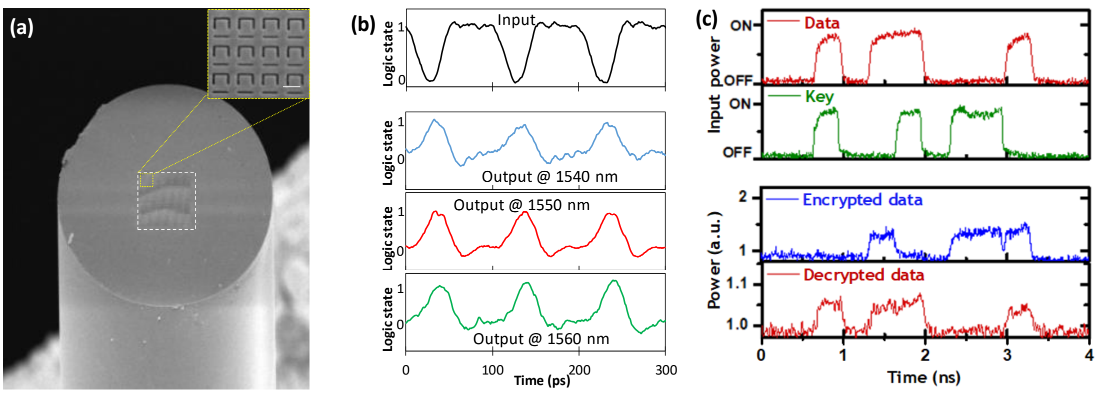

Figure 1. **In-fiber coherent data processing with plasmonic metamaterial and classical light**. (a) SEM image of a cleaved fiber end-facet covered with plasmonic metamaterial (inset: SEM image of the nanostructure with 500 nm scale bar); (b) NOT function where 0111 input signals (black) are inverted to 1000 (colours) by coherent absorption at 40 Gbit/s for 3 telecoms wavelengths (colors); (c) Data and Key signals that are encrypted and decrypted by interaction on a metamaterial coherent absorber at a data rate of 3 Gbit/s.

II. RESULTS

The metamaterial is a two-dimensional array of asymmetric split-ring apertures in a subwavelength thickness gold film deposited on the cleaved end-facet of a fiber, Fig. 1a. Geometry and nanostructure dimensions are adapted to the wavelength used: classical experiments are done in the telecom C-band, while quantum experiments are conducted at 810 nm wavelength. The metamaterial-coated fiber is coupled to a second cleaved optical fiber either by using two microcollimator lenses or just by attaching fibers. Finally, the device is encapsulated in a metal housing.

The optical response of a metamaterial absorber can be altered from almost total absorption to almost total transmission, when illuminated by two counter propagating travelling waves. By controlling the phase retardation between two input waves, all-optical switching and, consequently, signal processing functions can be implemented. We demonstrate this by inserting a fabricated metadevice in a fully-fiberized Mach-Zehnder interferometer, where the phase retardation is controlled by an electro-optical modulator [3]. All-optical operations corresponding to logical functions AND, XOR and NOT (Fig. 1b) are realized at bitrates from 20 kbit/s up to 40 Gbit/s and at wavelengths between 1530 and 1565 nm (C-band). Selective absorption and transmission of 1 ps laser pulses and generation of 1 ps dark pulses is also demonstrated, implying a signal processing bandwidth of at least 1 THz [4].

Based on dissipative metamaterial logic gates, we demonstrate secure optical communication with information encrypted and decrypted in an all-optical telecommunication fiber network with mutually coherent signal channels, Fig. 1c. Sender (Alice) generates an encrypted signal by mixing mutually coherent Data and Key signals in a first coherent optical gate (metadevice) and transmits the encrypted signal and the key through separate channels. Receiver (Bob) uses a second coherent optical gate to eliminate the key from the encrypted signal and recovers the original data. An eavesdropper Eve cannot recover the data from one channel alone.

Nonlinear optical fibers, that yield an intensity-dependent optical phase shift by self-phase modulation or cross-phase modulation, can be used to control coherent absorption in a metamaterial absorber. This permits perfect nonlinear absorption, where changes in the intensity of input light can increase absorption to 100% or reduce it to 0%. We demonstrate that this enables optical power limiting, noise suppression, pulse cleaning, pulse splitting and transfer of intensity modulation from one wavelength to another.

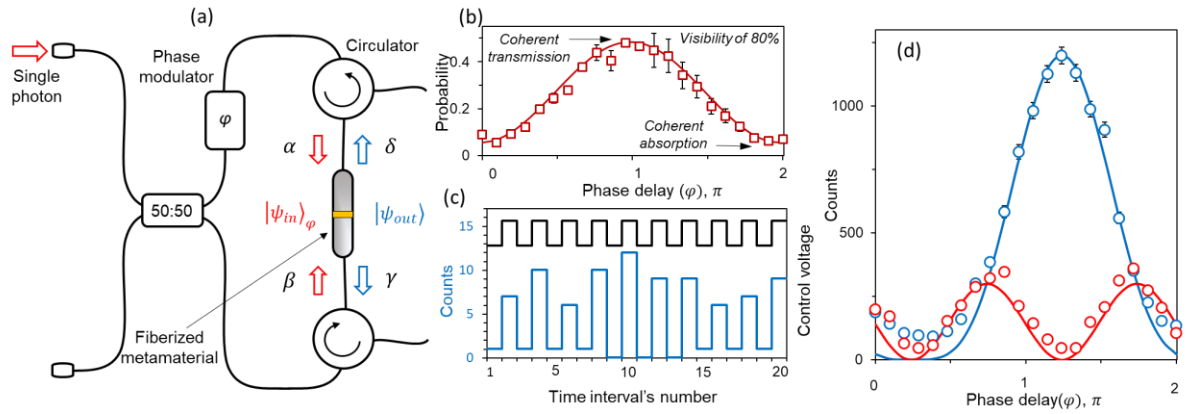

Figure 2. **Coherent single photon processing in a fiber quantum network**. (a) Simplified scheme of a fiber quantum network containing a metamaterial package and interrogated by heralded single photons. By controlling the phase retardation between two arms of the network we can either smoothly control the single-photon absorption probability (b) or perform single-photon switching by rapidly driving the system between regimes of coherent absorption and coherent transmission (c). Time interval in (c) is equal to 24 ms. (d) Demonstration of independence of the output single photon state on its input state done in a double interferometer scheme (similar to the scheme in Fig. 2a but with removed circulators; input and output ports are coincided). Single-photon counts recorded by the detectors placed at upper-left (blue circles) and bottom-left (red circles) port of the 50:50 beamsplitter in Fig. 2a are in a good agreement with theoretical curves (blue and red lines).

In contrast to conventional optical nonlinearities, coherent perfect absorption allows intensity-independent control over absorption of light, even at a single-photon level, opening new ways for coherent processing of quantum light. Single-photon coherent perfect absorption arises from the phase sensitive interference of single photon with itself in the presence of an absorber resulting in absorption probability control, in the ideal case, in the range from 0 to 1, which can be realized in a fully fiberized network containing the metamaterial package, Fig. 2a. The wavefunction of heralded single photons, produced via spontaneous parametric down conversion, is split on the 50:50 beamsplitter and recombined on the metamaterial absorber. By continuously altering the phase retardation between two optical paths, we smoothly shift between quantum regimes of coherent absorption and coherent transmission, Fig. 2b. By rapidly shifting between these regimes, a single-photon coherent switch is realized, Fig. 2c, with access to all-optical logical gates operating at the lowest possible energy.

Deeper consideration of the phenomenon reveals the sensitivity of the metamaterial to the quantum state of a single photon occupying two spatial modes (two arms of the interferometer). The metamaterial completely absorbs a photon with a symmetric superposition of the two-mode state, while it transmits a photon with an anti-symmetric state, acting as a quantum state filter. By performing simultaneous scanning of the input state and measuring the output state of the photon, we show that, indeed, the state of the photon, passed through the metamaterial, is well-defined and does not depend on its input state, Fig. 2d.

Extension of this concept to the case when metamaterial is illuminated by light beams at weak coherent states allows to perform quantum states comparison scheme: Light is totally absorbed when input states are identical, while light is transmitted without losses when input states are out-of-phase. Thus, detection of a single photon at the metamaterial output ports indicates that two input states are opposite in phase. Moreover, coincidence detection can enhance the validity of the measurement, overcoming dark count noise. We discuss the implementation of quantum states comparison for the purposes of quantum states discrimination and quantum key distribution.

III. Conclusion

In conclusion, we demonstrate that coherent fully-fiberized networks with integrated metamaterials are suitable for light manipulation both in classical and quantum regimes, opening new ways for all-optical data processing directly in the fiber environment.

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