A plasmonic route towards the energy scaling of on-chip integrated all-photonic phase-change memories

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ABSTRACT

Phase-change photonic memory devices, conventionally implemented as a thin layer of phase-change material deposited on the top of an integrated Si or SiN waveguide, have the flexibility to be applied in a widely diverse context, as a pure memory device, a logic gate, an arithmetic processing unit and for biologically inspired computing. In all such applications increasing the speed, and reducing the power consumption, of the phase-switching process is most desirable. In this work, therefore, we investigate, via simulation, a novel integrated photonic device architecture that exploits plasmonic effects to enhance the light-matter interaction. Our device comprises a dimer nanoantenna fabricated on top of a SiN waveguide and with a phase-change material deposited into the gap between the two nanoantenna halves. We observed very considerably increased device speeds and reduced energy requirements, of up to two orders of magnitude, when compared to the conventional structure.

Key words: photonic memory, plasmonic, nanoantenna, phase-change driven plasmonics

1. STRUCTURE CONFIGURATION AND OPTICAL BEHAVIOR

Integrated phase-change photonic devices have recently found exciting applications in the areas of memory, arithmetic and logic processing and even neuromorphic computing [1-4]. Reducing the power consumption and increasing the speed of such devices is thus of much interest and importance. We attempt to do this by here using the proposed structure of Fig. 1(a-b), which consists of a dimer nanoantenna, composed by two symmetrically placed silver nanodiscs, of 75 nm radius and 30 nm thickness, with an edge-to-edge gap of 40 nm, fabricated on top of a 330 nm x 1300 nm SiN waveguide. A TE-mode (wavelength λ = 1550 nm) pulse traveling along the waveguide initiates a dipolar plasmonic resonance, with the consequent magnification of the electric field in the gap region. A convenient placement of $Ge_2Sb_2Te_5$ (*GST*) in the nanoantenna gap modulates the resonance strength (see Fig. 1(c)), due to the sensitivity of such structure to the chemical environment, and henceforth the amount of absorbed and scattered light, tuning the waveguide optical attenuation as a function of the GST crystal fraction *X*, owing to the phase-dependent GST dielectric function. The device exhibits a transmission *T* of 0.943 for amorphous GST, and T = 0.799 for crystalline GST.

2. MODELING OF WRITE AND ERASE OPERATIONS

2.1. WRITE. Starting from the fully crystallized GST, the delivery of a single 1 mW, 2 ns rectangular pulse is capable of melting ~82% of the GST cell. The subsequent extremely rapid thermal quenching (1/e thermal decay calculated to be 0.6 ns) vitrifies the molten phase, resulting in an optical contrast $((T_{am}-T_x)/T_{am})$ variation of 12.1%. Slightly higher power (1.2 mW) allows to reach a *X* value of 88% in less than 500 ps (with a consequent read signal of T = 0.815).

2.2 ERASE. Recovery of the crystalline phase here uses a decreasing power double-step pulse, to compensate for the absorption increase during the recrystallization process. Starting from $X \approx 18\%$, we deliver a rectangular pulse of 1.5 mW x 1.5 ns, which initiates the melting process. We then deliver a

1.2 mW to 0.5 mW, 15 ns linearly decreasing pulse, which results in mainly growth-dominated recrystallization (from the external surfaces towards the inner region). After the pulse delivery, accounting of a total energy of 15 pJ, the system is fully recrystallized (X = 98%, T = 0.801)

2.3 MULTI-LEVEL STORAGE. Interruption of the *erase* pulse before its completion allows the retrieval of partially crystallized states. In particular, we obtain values of X of 18%, 44%, 72%, and 98% by stopping the *erase* sequence at 10.2, 12.4, 13.8, and 16.5 ns respectively. We observe a related optical contrast separation of ~4% (more specifically, 12.1%, 8.3%, 4.1%, and 0.2% respectively), thus enabling the achievement of multi-level (*ML*) storage. We've found that it is sufficient to use a preceding *overwrite* pulse, of 1 mW, 2 ns, to return to X = 18% from any of the considered levels. Our results are displayed in Fig. 1(d).

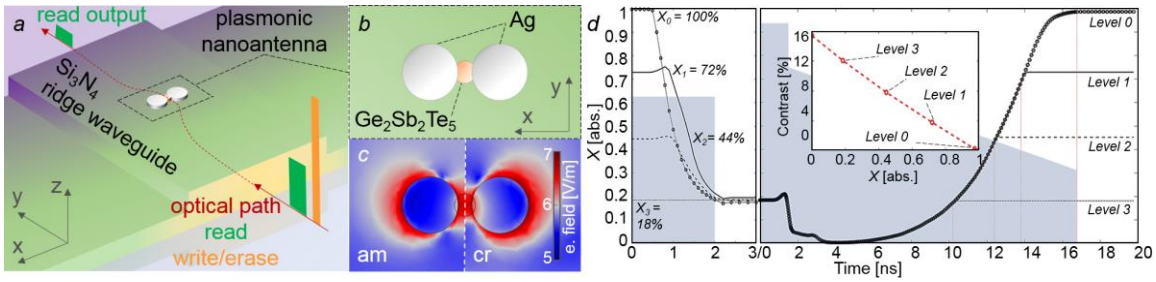

Fig. 1 Plasmonically-enhanced phase-change optical cell: architecture, principles and operations. (a) Structure configuration and operating principles. The disc dimer nanoantenna (b, top view), comprising of a GST inclusion within the gap, is fabricated on top of a SiN waveguide. With an optical pulse traveling along the waveguide, a dipolar resonance is initiated on the nanoantenna, which magnifies the electric field in the gap region (c, electric field [V/m]). The structure's resonance is tailored by the GST phase, yielding a measurable difference of the waveguide transmission. Stored information is thus encoded in the GST crystal fraction X: it modulates the waveguide optical attenuation (*read*, performed through a low power signal), and can be modified via the same optical path by use of higher power pulses. (d) Plots of X *vs time* during the *write*/*erase* operations. Each line corresponds to a unique initial or final X value; the greyed area provides a view of the optical pulse profile. (left) *write*/*overwrite*, using a 1 mW / 1 ns pulse. (right) *erase* operation, by use of a double-step pulse composed of an initial pulse of 1.5 mW / 1.5 ns followed immediately by a pulse with linearly decreasing power (1.2 mW to 0.5 mW) and 15 ns duration. (inset) optical contrast vs X, showing a quasi-linear dependency through the whole range.

3. CONCLUSION

A novel plasmonically-enhanced integrated phase-change photonic device structure has been introduced and simulated. Results suggest a very significant increase in device switching speed, and a reduction in power consumption, should be achievable using such a structure. Fabrication and testing of our proposed architecture are currently being carried out.

ACKNOWLEDGEMENTS

CDW thanks EPSRC for funding by way of the ChAMP and WAFT grants (EP/M015130/1 and EP/M015173/1). EG acknowledges funding via the EPSRC CDT in Metamaterials (EP/L015331/1).

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