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MWP true time delay implemented in PbS-SU8 waveguides

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ABSTRACT

A new kind of microwave true time delay (TTD) device based on the dispersion of PbS colloidal quantum dots (QDs) in the commercially available photoresist SU8 is presented. For this purpose PbS-SU8 nanocomposites are integrated on a silicon platform in the form of ridge waveguides. When these structures are pumped at wavelengths below the band-gap of the PbS QDs, a phase shift in an optically conveyed (at 1550 nm) microwave signal is performed and therefore a temporal delay is produced. Furthermore, results are improved by implementing a novel ridge bilayer waveguide composed by a PbS-SU8 nanocomposite and a SU8 passive layer that reduces the losses due to the pump beam, and hence to improve the excitation of the QDs. The resulting device shows potential benefits respect to the current TTD technologies since it allows a fast tunability of the temporal delay by controlling the pump power and a high level of integration due to its small size and the material used.

Keywords: True time delay, nanocomposites, Microwave Photonics, polymer waveguides.

1. INTRODUCTION

Microwave photonics (MWP) [1] has emerged over the last decades as an exciting discipline based on the transportation and processing of microwave (MW) signals over optical carriers in order to carry out radiofrequency (RF) functions. MWP enables the broadband, interference-immune and low loss transport and processing of RF signals together with the possibility of performing multiple applications that are complex and even impossible to carry out with traditional electrical approaches, improving the performances of broad range of fields, such as wireless communications, radar, signal filtering or sensing [2]. Examples of these applications include arbitrary waveform generation, tunable and reconfigurable filtering, optoelectronic oscillators or beam steering are based on more basic functions such as phase shifting (PS) or true time delay (TTD) [3], and MWP solutions let broadband operation and enhanced tunability on TTD and PSs. Moreover, the MWP can be integrated in photonic integrated circuits (PICs), field known as integrated microwave photonics (IMWP), in order to provide additional advantages as compactness, easiness of reproducibility and limited costs [4].

In this way, one fundamental key block of several MWP functionalities, for example in tunable filtering, is the true time delay (TTD) device, useful to overcome limitations of the conventional electrical approximations, like frequency- dependent losses, or to enable ultra wideband operation. Examples of photonics TTDs architectures are the use of optical fibre links along with a tunable laser to feed a phase array antenna system [5], the use of semiconductor optical amplifiers (SOAs) [6] or microring resonators [7]. Nevertheless, these implementations showed some drawbacks, for instance optical links lack of flexibility, SOAs showed RIN limitations and distortions and microring resonators have a narrowband behaviour.

To overcome those constraints a novel technology approach that is able to integrate photonic TTDs with organic waveguides implemented in silicon platforms is proposed. This technology consists in nanocomposites formed by the dispersion of colloidal quantum dots (QDs) in polymers [8]. This sort of multicomponent material is emerging as very suitable device for many photonic applications due to the combination of the QDs optical properties (room temperature emission and bandgap tunability) in addition to the technological properties of the polymers, i.e. deposition on films by different methods and patterning by UV or e-beam lithography. Here we propose the use of bidimensional bilayer SU8 waveguides, showed in Fig. 1 (a), formed by a QDs-SU8 layer and a SU8 cladding layer to implement a broadband, tunable and flexible MWP TTD.

2. EXPERIMENTAL SETUP AND WAVEGUIDE STRUCTURE AND FABRICATION

The nanocomposite used in this work is based on the dispersion of PbS QDs in the SU8 matrix. Nanocrystals were synthesized following the method proposed by Yu and Peng [9]. The QDs diameter was controlled to be around 4.5 nm in order to locate the exciton peak close to 1550 nm and thus providing absorption at this wavelength [10]. Afterwards, an appropriate ligand exchanged was developed on the QDs in order to allow a good dispersion of the nanocrystals in γ-butyrolactone (usual solvent of SU8) [11]. Then, straight ridge waveguides were fabricated over a SiO_2/Si substrate (t=2μm) upon UV exposure following the standard procedure explained at [12]. The filling factor (*ff*) of nanocrystals in the polymer was set to be around 10^{-3} to obtain a good compromise between QD excitation and light absorption [8]. Waveguides consist of a ridge bilayer structure composed by a PbS-SU8 nanocomposite (bottom layer) and a SU8 (top layer), as it is shown in Fig. 1. For this purpose both materials (PbS-SU8 nanocomposite and SU8 respectively) were subsequently spin coated on the substrate and in two steps at 65ºC and 95ºC for two minutes each with the intention to achieve at the end of the process a bilayer film of 4 μm (2 μm each layer) These films were later exposed to a standard UV process (UV illumination+development) in order to pattern consecutive sets of w=4, 6, 8, 10 and 20 μm wide lines with 50 and 100 μm of separation between consecutive lines and sets respectively.

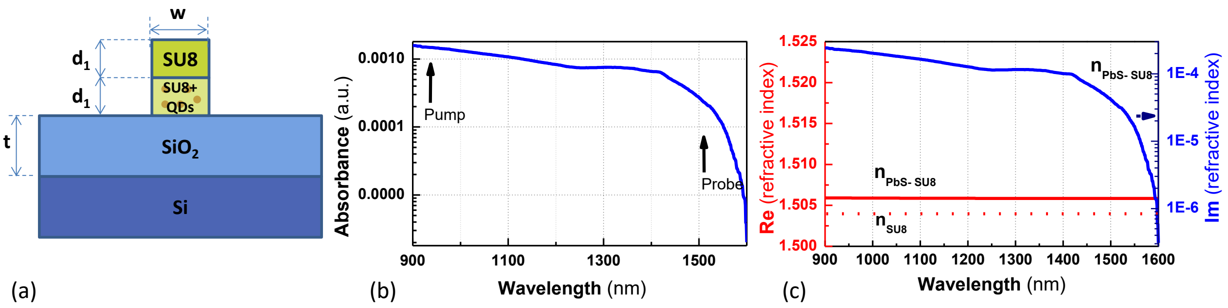

Fig. 1. a) Schematic view of the waveguide studied; b) absorption spectra of the PbS-SU8 QDs at pump (980 nm) and probe (1550 nm) wavelength and c) real (red solid line) and imaginary (blue solid line) parts of the PbS-SU8 (ff=0.01) refractive index and real (red dashed line) part of the SU8 refractive index.

The setup used to perform the measurements is shown in Fig. 2. A 1550 nm continuous-wave (CW) laser is electro-optically modulated with a microwave tone (10 MHz-25 GHz) generated by a vector network analyser (VNA). Then, this double side band signal is mixed together with a 980 nm CW pump laser at a wavelength division multiplexer (WDM). At the output of the WDM the two beams are injected into the waveguide with the aid of a tapered fibre [13]. At the output edge of the waveguide, light is collected with another lensed fibre and pumped into another WDM that separates the 1550 and 980 nm signals. The 1550 nm signal is photodetected and the detected electrical signal is injected to the VNA where its magnitude and phase are measured, calculating the S_{21} parameter that relates the detected and the generated MW signals.

The working principle of the TTD device is based on the saturable absorption of the QDs when they are pumped below their bandgap, where the nanocrystals show strong absorption, as can be seen in the inset of Fig. 1 (b). Therefore, when the light at 980 nm excites the QDs it is expected to affect the group index of the signal travelling at 1550 nm, producing a phase change in the MW signal and in consequence a temporal delay.

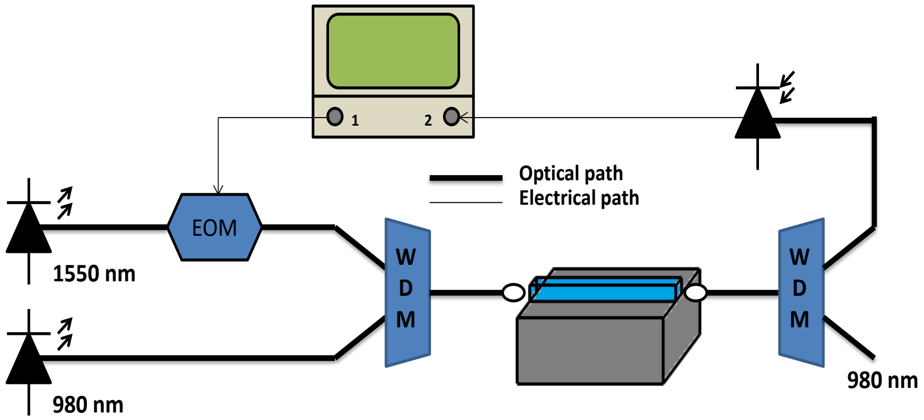

Fig. 2. Layout of the measurement setup.

3. EXPERIMENTAL MEASUREMENTS

Samples fabricated following the process explained before where tested as TTD by characterizing the microwave signal with the set-up explained in the last section. Temporal delay suffered by the RF signal along its entire bandwidth (10 MHz-25 GHz) was calculated by increasing the pump power progressively while the power of the signal wave is kept constant.

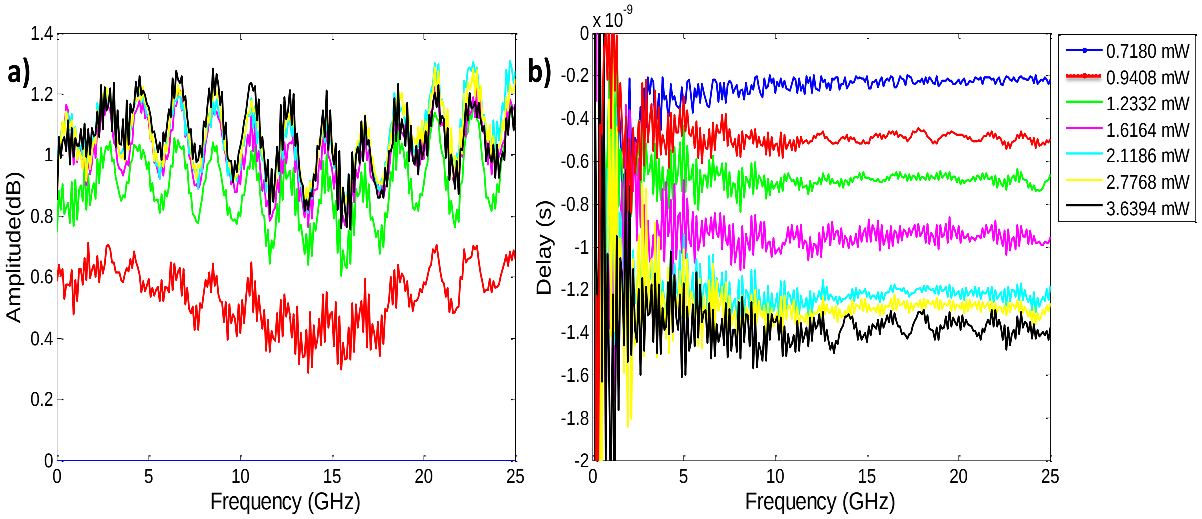

Fig. 3. a) amplitude responses as a function of the microwave frequency in the 20 μm wide 6 mm long SU8 bilayer waveguide by pumping with the 980 nm laser for different coupled powers to the input edge of the structure normalized to the smallest pump power trace and b) time delay as a function of the microwave frequency for different pump powers.

Different waveguides widths and lengths are tested, concluding that the narrower/longer the waveguide the higher the delay produced. The best results, showed at Fig. 3 (b), were produced by the 20 μm wide 6 mm long waveguide. The temporal delay shows distortion at low frequencies caused by a small SNR at those frequencies, as can be seen in Fig. 3 (a), where the normalized detected signal power is represented for different coupled pump powers. In addition, temporal delay increases with the pump (see Fig. 3 (b)), and reaches saturation for pump powers higher than 2 mW, due to the saturation of the QDs absorption. The higher the pump power the better the delay line and the amplitude of RF signal, proving that the absorption of the QDs is being saturated by the pump wave rather than the signal wave. Besides, the ripples of the amplitude response are lower than 0.5 dB maintaining the amplitude almost constant along the entire bandwidth. The temporal delay value obtained could be improved modifying the design of the sample to obtain an enhanced confinement of the light and a better excitation of the QDs. These strategies will be considered in further research.

4. CONCLUSIONS

In this work a novel approach to implement a TTD device based on PbS-SU8 nanocomposites integrated into silicon platforms is reported. For this purpose it was firstly necessary to perform the appropriate ligand exchange to disperse the QDs homogeneously in the SU8 matrix. Then, by exploiting the lithographic properties of SU8 an active ridge PbS-SU8 waveguides are implemented with the intention to produce a to modify the group refractive index of an optical carrier at 1550 nm travelling along the structures by pumping the PbS QDs; and as a consequence producing a temporal delay in the MW signal that modulates the optical carrier. Furthermore, a bilayer ridge structure consisting of a bottom PbS-SU8 nanocomposite and a top SU8 passive cladding is proposed with the idea to use the top cladding to decrease the losses of the pump beam travelling through the structure and hence, improving the excitation of the nanocrystals and the temporal delay. The potential advantages of the proposed structures rely on a high level of integration and a continuous and fast tunability with the pump under broadband operation.

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REFERENCES

[1] J. Capmany and D. Novak, "Microwave photonics combines two worlds," *Nat. Photon.*, vol. 1, pp. 319–330, 2007.

[2] J. Yao "Microwave photonics," *J. Lightwave Technol.*, vol. 27(3), pp. 314 -335, 2009.

[3] J. Capmany, J. Mora, I. Gasulla, J. Sancho, J. Lloret, and S.Sales, “Microwave photonic signal processing,” *J. Lightwave Technol.*, vol. 31(4), pp. 571-586, 2013.

[4] D. Marpaung, C. Roeloffzen, R. Heideman, A. Leinse, S.Sales, and J. Capmany, “Integrated microwave photonics,” *Laser & Photon. Rev.*, vol. 7(4), pp. 506-538, 2013.

[5] E. Udvary, T. Berceli, "New microwave/milimeter wave true time delay device utilizing photonic approaches," *in Proc. 2010 European Microwave Conference (EuMC),* Paris, France, September 2010, pp. 121-124.

[6] Y. Minamoto, M. Matsuura, "True time delay beamforming using semiconductor optical amplifier and tunable dispersion medium," *in Proc. IEEE IC-NIDC 2014*, Beijing, China, 2014, pp. 164-167.

[7] P. A. Morton, J. B. Khurgin, Z. Mizrahi, S. J. Morton, "High SFDR 'Super-ring' microresonator based TrueTime-Delay (TTD)," *in Proc. 2014 AVFOP IEEE*, Atlanta, USA, 2014, pp. 27-28.

[8] I. Suárez, H. Gordillo, R. Abargues, S. Albert and J.P. Martínez-Pastor, "Photoluminescence waveguiding in CdSe and CdTe QDs-PMMA nanocomposite films," *Nanotechnology*, vol. 22(43), p. 435202, 2011.

[9] W. W. Yu and X. Peng, “Formation of high-quality CdS and other II–VI semiconductor nanocrystals in noncoordinating solvents: Tunable reactivity of monomers,” *Angew. Chem. Int. Ed.*, vol. 41(13), pp. 2368–2371, 2002.

[10] A. L. Ricchiuti, I. Suárez, D. Barrera, P. J. Rodríguez-Canto, C. R. Fernández-Pousa, R. Abargues, S. Sales, J. Martínez-Pastor and J. Capmany,"Colloidal quantum dots-PMMA waveguides as integrable microwave photonic phase shifter", *IEEE Photon. Technol. Lett.*, vol. 26, no. 4, pp. 402-404, 2014

[11] H. Gordillo, I. Suárez, R. Abargues, P.J. Rodríguez-Cantó, S. Albert and J.P. Martínez-Pastor, "Polymer/QDs nanocomposites for waveguiding applications," *J. Nano Mat.*, vol. 2012, p. 960201, 2012.

[12] MicroChem Corp., http://www.microchem.com/Prod-SU-8_KMPR.htm

[13] L. Arques, A. Carrascosa, V. Zamora, A. Díez, J. L. Cruz and M. V. Andrés, "Excitation and interrogation of whispering-gallery modes in optical microresonators using a single fused-tapered fibre tip," *Opt. Lett.*, vol. 36(17), pp. 3452-3454, 2011.