EPJ Web of Conferences **266**, 08011 (2022) https://doi.org/10.1051/epjconf/202226608011
EOSAM 2022

Nonlinear pulse routing in plasmonic couplers

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Abstract. We present a system able to discriminate pulses according to their duration with potential applications in all-optical signal multiplexing. The device is based on a directional coupler with nonlinear cores and metallic claddings with dimensions in a nanometric scale. Simulations are carried out using the FDTD technique for ultrashort pulses of femtosecond order. It is shown that the device is able to separate such pulses respect to a time-width threshold which depends on the total energy of the pulse.

1 Introduction

Modern technology pursues the increase of communication capabilities requiring from fast processing systems to discriminate and route information and also from miniaturized components leading to a high encapsulation rates. In such a way, plasmonics has come into play to put optical devices into the nanoscale [1] even though important drawbacks, as the high losses associated to such devices, have to be overcome.

The implementation of all-optical operations is very important in order to achieve high processing speed and so exploiting nonlinear properties is one of the the most valuable resources available at the time. In such a way there is a great interest on the use of pulses to increase optical power density and induce the nonlinear response with a reasonable power. Up to now different nonlinear systems using metals have been studied mainly in the continuous wave regime (CW), particularly the nonlinear directional coupler for optical power switching [2]. Nevertheless, modeling such systems for their use with ultrashort pulses has proved to be difficult as it is revealed by the scant number of works available at the moment on the matter, which additionally deal with quite simple systems as metal-dielectric interfaces [3, 4] or single slot waveguides [5, 6].

In this work we present a device to perform all-optical switching based on the input pulse duration. In a previous work [7] we already explored the possibility of all-optical switching based on total pulse energy. The mechanism presented here is an alternative operation mode for the same device which in principle would not require from any physical modification to operate in one or another way, being consequently more versatile.

2 Device description

The directional coupler is assumed to lie in the plane XZ, being z the propagation direction, and is formed by two slot waveguides. The two dielectric cores show the nonlinear Kerr response and are embedded into metallic linear claddings. The field is assumed to be a TM mode with one magnetic and two electric components, H_y, E_x and E_z. A reference wavelength $\lambda_0 = 800\,\text{nm}$ is chosen and normalized units used, scaling the spatial coordinates by the wavenumber $k_0 = 2\pi/\lambda_0$ and the time by the reference frequency $\omega_0 = 2\pi c/\lambda_0$, being c the vacuum speed of light. This means that a space normalized unit equals to about 127 nm while a normalized time unit equals to 0.42 fs.

Cores are modeled using an instantaneous response. On the other hand metallic claddings are modeled by the *additional differential equation* (ADI) technique [8] using a classical Drude model dependent on two parameters, the plasma frequency and the electronic collision frequency (which accounts for losses). Those parameters for silver at the reference wavelength are $\omega_p = 1.30 \times 10^{16}$ Hz and $\Gamma = 2.93 \times 10^{13}$ Hz. The computation domain is surrounded by proper perfect matching layers (PML) and a source is implemented using the Total field/Scattered field technique, to generate pulses of Gaussian shape (spatial as well as temporal) at one of the cores (first core).

Energy of pulses is measured at a particular z-position in any of the cores by integrating in space (transversal coordinate, x) and time the power flux in the propagation direction, i.e. the z component of the Poynting vector $S_z = E_x H_y$.

3 Operation results

The key of the device operation is the ability of the coupler to pass energy to the second core from the first one (the excited one) after propagation along a distance named beat length (linear regime). For the simulated coupler this

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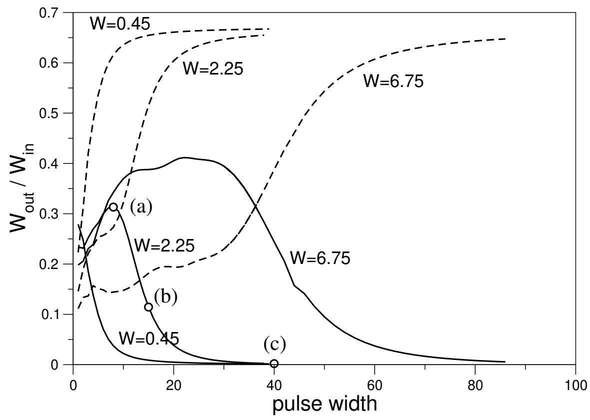

Figure 1. Normalised output energy at the excited core (solid lines) and second core (dashed lines) against input pulse width for three different energy pulses. Points (a), (b) and (c) correspond to cases with the same label in figure 2.

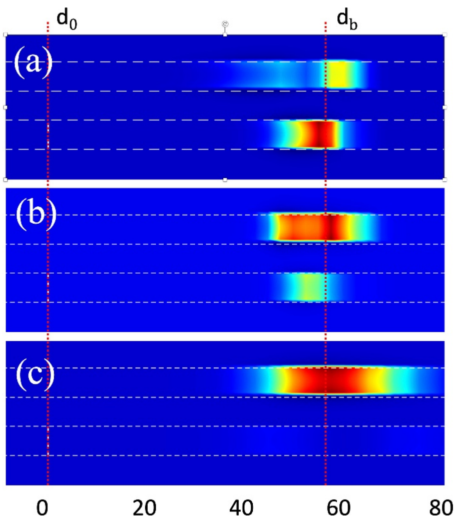

Figure 2. Simulation for three pulses of energy $W = 2.25$ and different time width: a) $\Delta t = 10$, b) $\Delta t = 15$, c) $\Delta t = 40$. Lines d_0 and d_b mark the source and output positions.

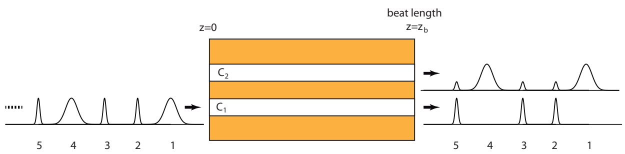

Figure 3. Sketch of the device operation to discriminate different time-width pulses.

length is about $z_b \sim 57$. When pulses have enough energy a nonlinear response is triggered, beat length changes and inter-core energy transmission is incomplete up to the point that it is fully suppressed if pulse energy is enough (energy switching) [7]. Pulse time-width also influences coupling as power density changes (if total energy is the same) and so it is also expected a change in the switching response when the pulse duration is modified. Actually, for a fixed energy, a longer pulse carries a lower density and so the system should work more as it were in a linear regime. This is clearly seen in figure 1 where the output energy after propagation for a beat length is plotted against the pulse duration for three different pulse energies. The output at the excited core (continuous lines) is large for low duration pulses as the system operates in a nonlinear regime and almost all the energy remains in the excited core. Transferred energy (dashed lines) is consequently low. Increasing the pulse duration makes the solid curves to decrease to zero as the nonlinear effect is weaker and a larger fraction of the energy passes to the second core. The effect takes place at larger pulse-width for high pulse energy as the nonlinear response depends on energy density. Optical losses are responsible for a total output energy fraction less than the unity (see figure 1, but due to the short length of the device (beat length around 7.5 μm) such losses are assumable (about 30% of the input energy). In figure 2 we show a particular simulation for three pulses of the same energy but different time width illustrating the three switching regimes. In subfigure (a) a short pulse triggers the nonlinearity and the coupler only passes a fraction of the energy to the second core. In (b) the longer pulse makes a big amount of the energy to switch to the second core, reducing the signal at the output of the excited core. In the third case an even longer pulse produces a full energy transfer to the second core since it is now in a linear regime.

According to this system performance the device is useful to separate shorter pulses from larger ones as illustrated in figure 3. The time-width threshold for discrimination is determined by the total energy of pulses and can be adjusted according to the requirements of every particular case. Also this threshold can be easily reconfigurable (changing pulse energy) resulting a very versatile device.

We thank the support of MCIN of Spain through the projects PID2020-118613GB-I00 and PID2020-120484RB-I00, as well as Xunta de Galicia, Spain (grant ED431B 2021/22) and Generalitat Valenciana for the grant PROMETEO/2021/082.

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