SAND2017-8182C

Femtosecond Polarization Switching Using a Cadmium-Oxide-Based Perfect Absorber

Yuanmu Yang,[1,2] Kyle Kelly,[3] Edward Sachet,[3] Salvatore Campione,[1] Ting S. Luk,[1,2] Jon-Paul Maria,[3] and Igal Brener[1,2]

[1]*Sandia National Laboratories, Albuquerque, New Mexico 87185, USA*

[2]*Center for Integrated Nanotechnologies (CINT), Sandia National Laboratories, Albuquerque, New Mexico 87185, USA*

[3]*Department of Materials Science, North Carolina State University, Raleigh, North Carolina 27695, USA*

yuayang@sandia.gov

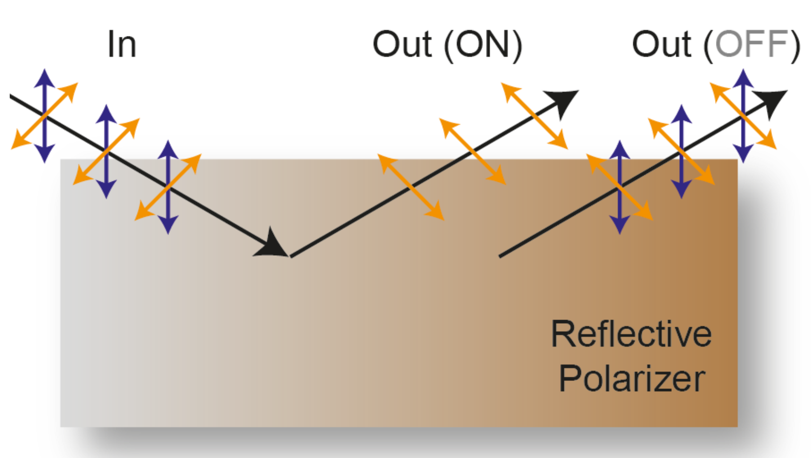
U.S. DEPARTMENT OF ENERGY

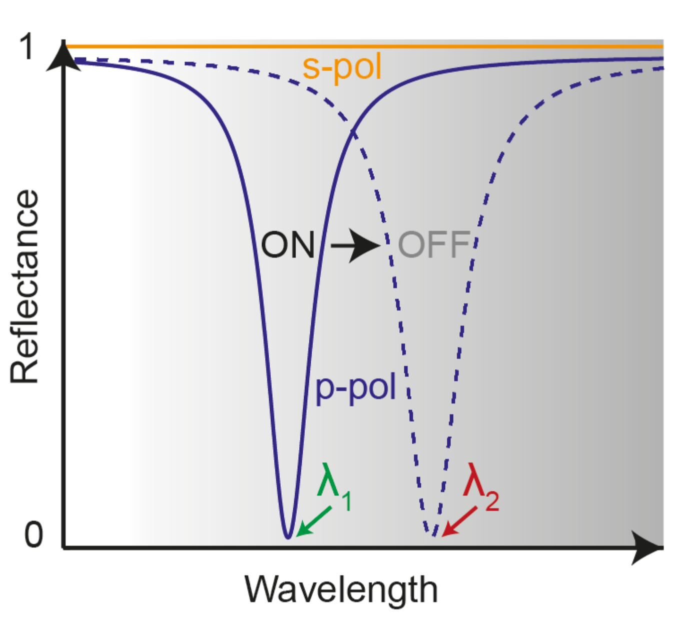
Office of Science

cint.lanl.gov

Introduction

Ultrafast control of the polarization state of light may enable a plethora of applications in optics, spintronics, and chemistry. However, conventional polarizing elements such as polarizers and waveplates are either static or possess only moderate switching speeds on the order of milliseconds. Femtosecond (fs) all-optical switching of light polarization has been proven challenging. Here, with the aid of high-mobility epitaxially-grown dysprosium-doped cadmium oxide (CdO) as the gateway plasmonic material[1], we realize a high-quality factor, polarization-selective Berreman-type perfect absorber[2–4] at a wavelength of 2.08 µm. Upon sub-bandgap resonant optical pumping, the perfect absorption resonance strongly redshifts due to the transient increase of the ensemble-averaged effective electron mass of CdO, leading to a giant *absolute p*-polarized reflectance change from 1.0% to 86.3%. The switching time is sub-picosecond and is governed by electron-phonon coupling. By combining the exceedingly high modulation depth with the polarization selectivity of the perfect absorber, we experimentally demonstrate a reflective polarizer with a polarization extinction ratio of 91 that can be switched on and off within 800 fs. The device can be fabricated on a wafer scale, does not require surface patterning, and is scalable from near- to mid-infrared frequencies.





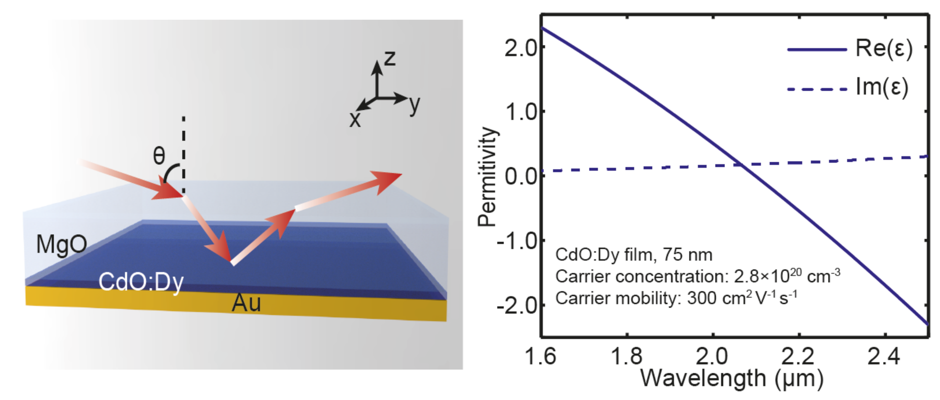
Schematic of a switchable reflective polarizer. (Top), Schematic illustration of an un-polarized beam reflecting from a switchable polarizer. The expected polarization states of the output beam, with the polarizer turned "ON" and "OFF", are shown on the right side. (Bottom), Depiction of a tunable optical cavity for the realization of a switchable polarizer. At the wavelength λ_1, the cavity is switched from a polarizer to a mirror when the polarizer is switched from "ON" to "OFF". In the meantime, at the wavelength λ_2, the cavity is switched from a mirror to a polarizer.

Dysprosium-doped Cadmium Oxide

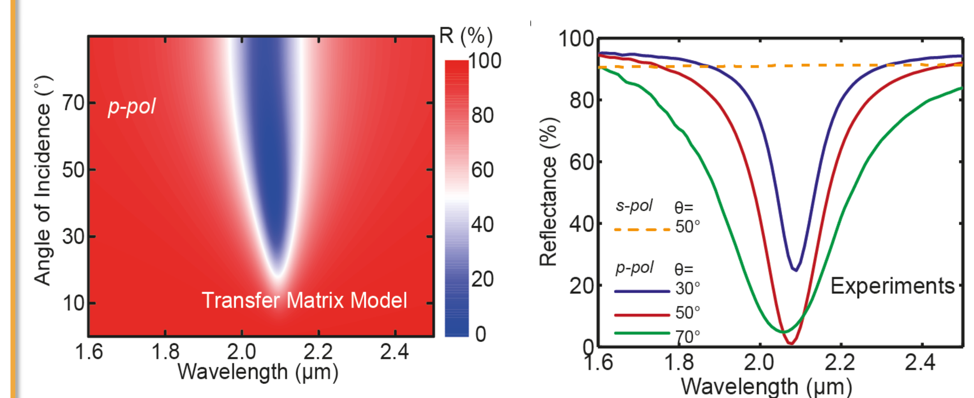
Material	Carrier Density [cm^{-3}]	Mobility [cm^2/V.s]	ENZ wavelength [µm]	ε″ at ENZ wavelength
CdO: Dy	9.94x10^{19}	474	3.61	0.19
CdO: Dy	3.7x10^{20}	359	1.87	0.13
AZO (2 wt%)	7.2x10^{20}	48	1.43	0.21
ITO (10 wt%)	7.7x10^{20}	36	1.40	0.69

Table 1. A comparison of losses of various plasmonic materials.

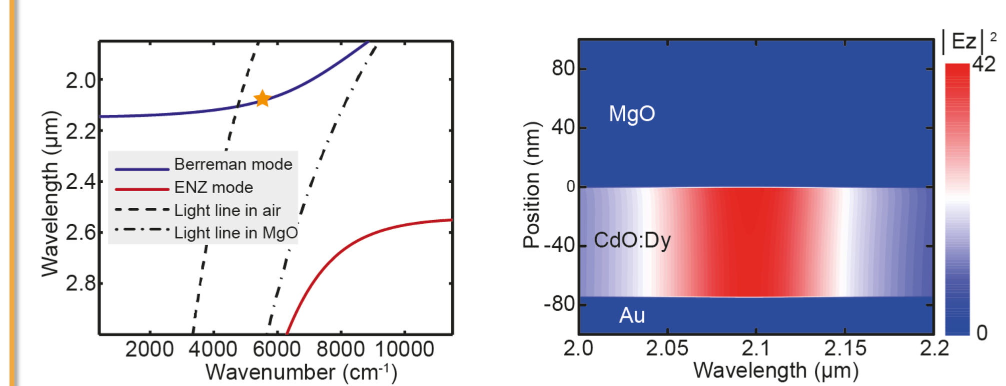
Static Optical Properties of the CdO-based Perfect Absorber



(Left), Schematic of the CdO-based perfect absorber. (Right), The real and imaginary parts of the permittivity of the CdO film.

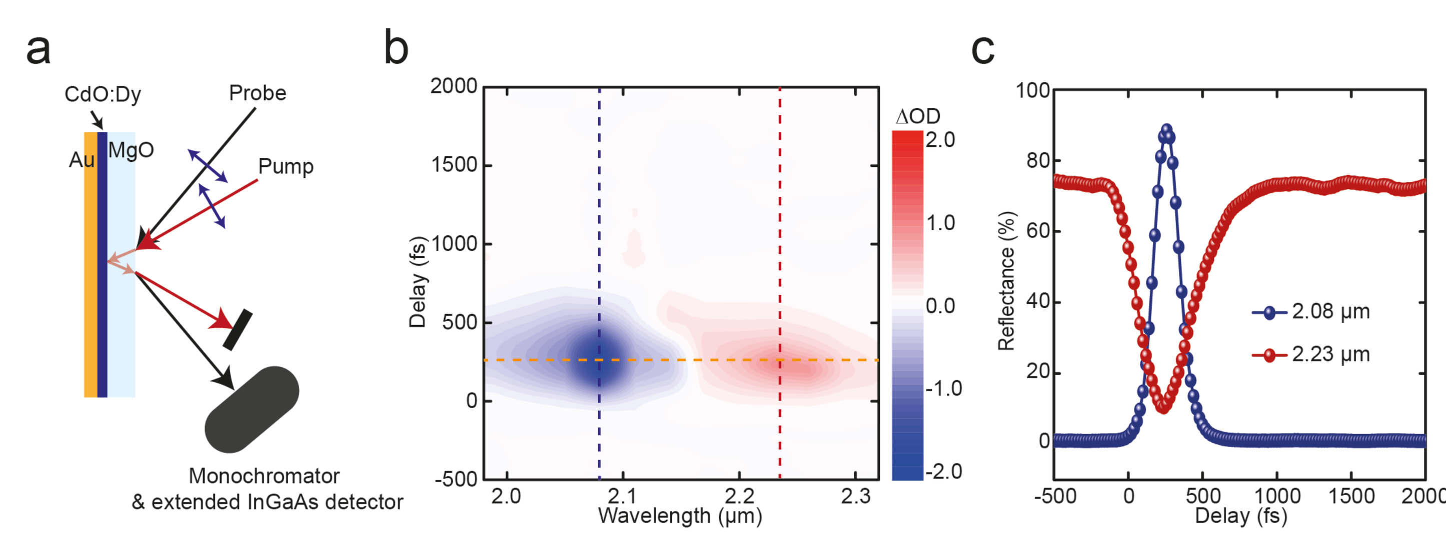


The calculated (Left) and measured (Right) reflectance spectra of the 3-layer structure for *p*-polarized light as a function of incident angles.

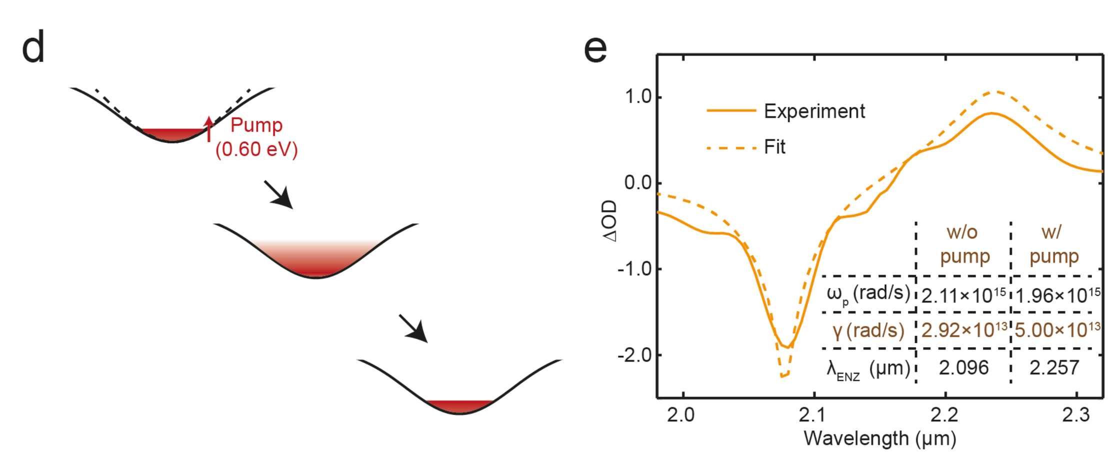


(Left), The dispersion relation of the 3-layer structure. (Right), The field distribution as a function of wavelength and the position within the sample

Ultrafast amplitude modulation via intraband pumping

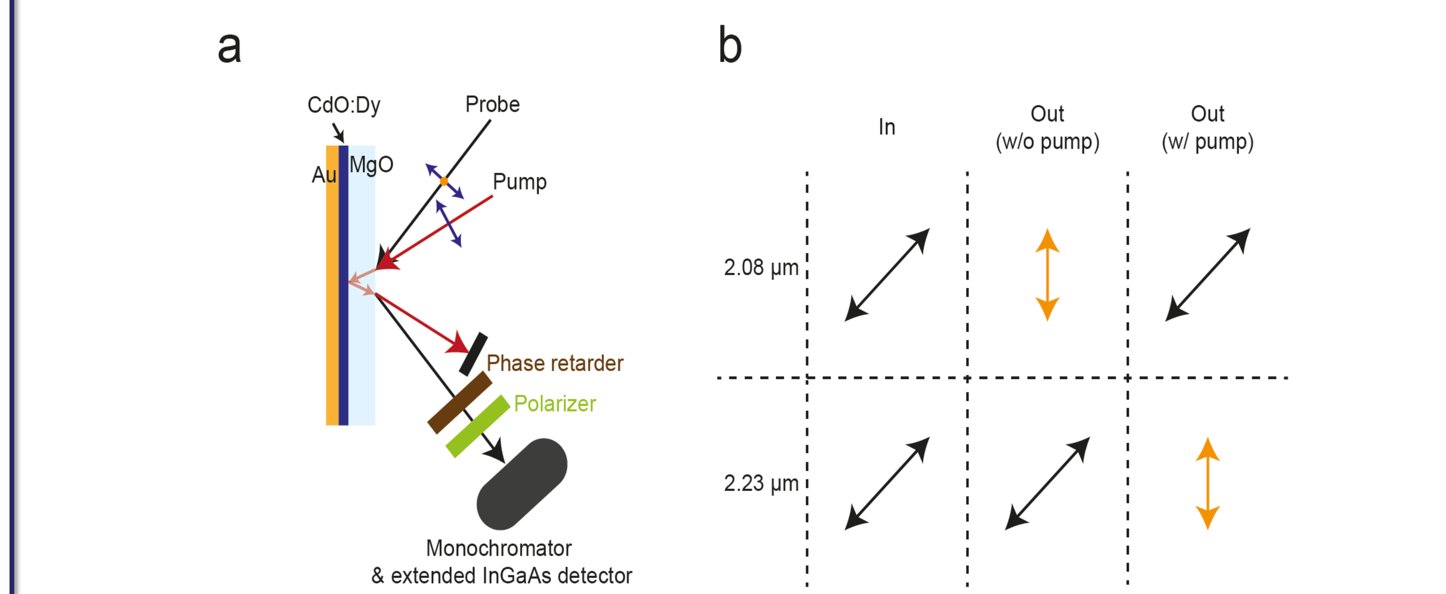


a, Schematic of the pump-probe measurement setup. b, The Δ*OD* map as a function of wavelength and delay time. c, Line-scans of the *absolute* reflectance of the sample versus delay time at 2.08 µm and 2.23 µm respectively (at the vertical blue and red dashed lines in panel b).

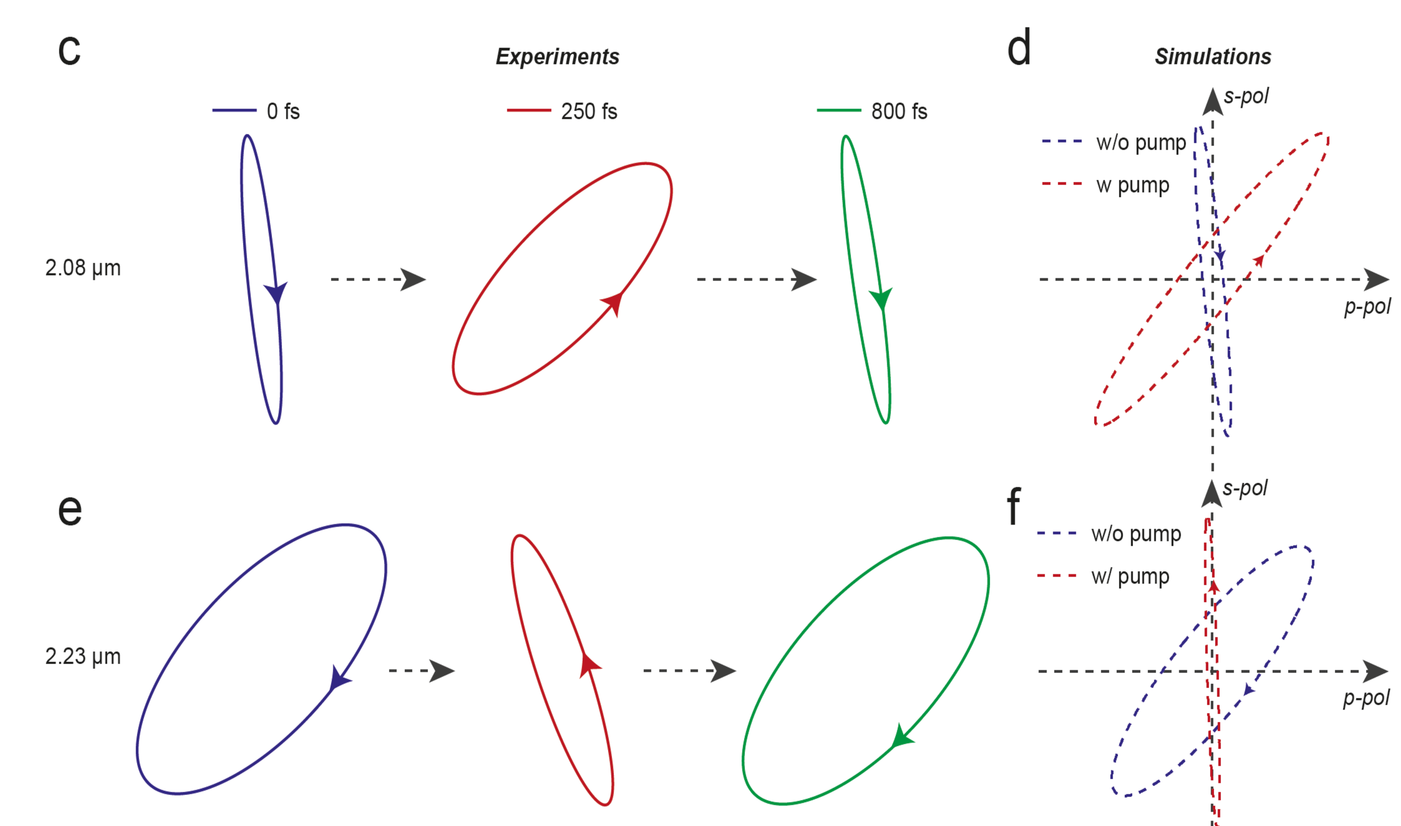


d, Schematic illustration of ultrafast dynamics in the CdO film, consisting of photoexcitation, hot electron redistribution and cooling. e, The experimental Δ*OD* spectrum along with the numerical fit (at the horizontal orange dashed line in panel b).

Polarization Switching



a, Schematic of the pump-probe measurement setup with the polarization analyzing unit included. b, The projected output polarizations for a linearly polarized input beam at 2.08 µm and 2.23 µm, and with and without pump, respectively.



c, The measured polarization ellipse of the reflected beam at 2.08 µm at delay time of 0 fs, 250 fs, and 800 fs, respectively. d, The simulated polarization ellipse of the reflected beam at 2.08 µm with and without pump, respectively. e-f, The measured and simulated polarization ellipse of the reflected beam at 2.23 µm, respectively.

Conclusion

To summarize, by taking advantage of a low-loss plasmonic material (CdO) with a stringently designed Berreman mode plasmonic cavity, we manage to construct a high Q-factor perfect absorber with an extremely high contrast dynamic tuning of the amplitude and polarization state of infrared light at a sub-picosecond time scale. The device could be implemented for the ultrafast control of numerous material excitations. The same design strategy can be applied to other high mobility materials at different spectral ranges, for example, InAs at THz frequencies. We could also envision solid state, electrically addressable and high contrast amplitude, phase or polarization modulators to be developed based on similar platform.

References:

1. Sachet, E. *et al.* Dysprosium-doped cadmium oxide as a gateway material for mid-infrared plasmonics. *Nat. Mater.* **14,** 414–420 (2015).
2. Luk, T. S. *et al.* Directional perfect absorption using deep subwavelength low-permittivity films. *Phys. Rev. B* **90,** 85411 (2014).
3. Tyborski, T. *et al.* Ultrafast Nonlinear Response of Bulk Plasmons in Highly Doped ZnO Layers. *Phys. Rev. Lett.* **115,** 147401 (2015).
4. Guo, P., Schaller, R. D., Ketterson, J. B. & Chang, R. P. H. Ultrafast switching of tunable infrared plasmons in indium tin oxide nanorod arrays with large absolute amplitude. *Nat. Photonics* **10,** 267–273 (2016).

Los Alamos NATIONAL LABORATORY EST. 1943

This work was supported by the U.S. Department of Energy, Office of Basic Energy Sciences, Division of Materials Sciences and Engineering and performed, in part, at the Center for Integrated Nanotechnologies, an Office of Science User Facility operated for the U.S. Department of Energy (DOE) Office of Science. Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Sandia National Laboratories