Highly isolated femtosecond magnetic fields driven by azimuthally polarized laser beams in nanoantennas

Rodrigo Martín-Hernández[1,*], Luis Sánchez-Tejerina[1], Enrique Conejero Jarque[1], Luis Plaja[1], Carlos Hernández-García[1]

[1]Grupo de Investigación en Aplicaciones del Láser y Fotónica, Departamento de Física Aplicada, Universidad de Salamanca, E-37008, Salamanca, Spain

*Email: rodrigomh@usal.es

Introduction

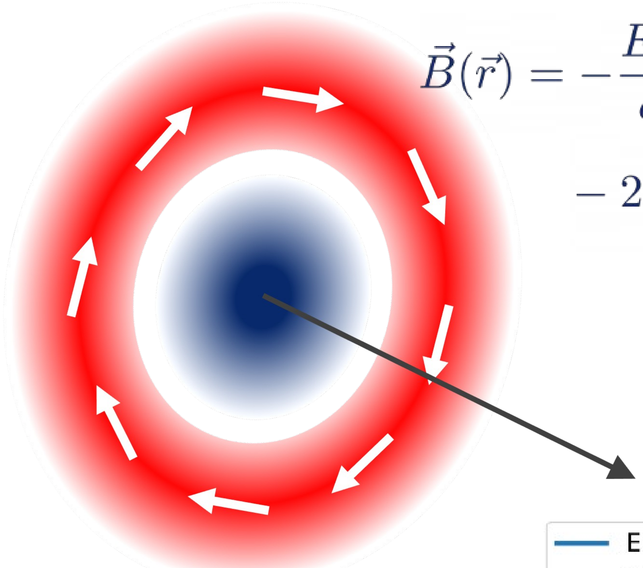
Ultarfast laser sources, have shown great potential to drive, observe and control ultrafast magnetism since the pioneering work on ultrafast demagnetization by Beaurepaire et al.[1] The development of ultrafast structured light beams[2], such as azimuthally polarized vector beams (AVB), has opened new perspectives in light-matter interactions in novel ways. For example it has been shown experimentally the generation of spatially tailored magnetic fields in semiconductors[3] or isolated magnetic fields in gold nanostructures[4]. Recently, It has been theoretically demonstrated how isolated circularly polarized magnetic fields offers the possibility of pure magnetic switching in ferromagnetic materials[5] or Néel vector oscillations in antiferromagnetic magnetic samples[6].

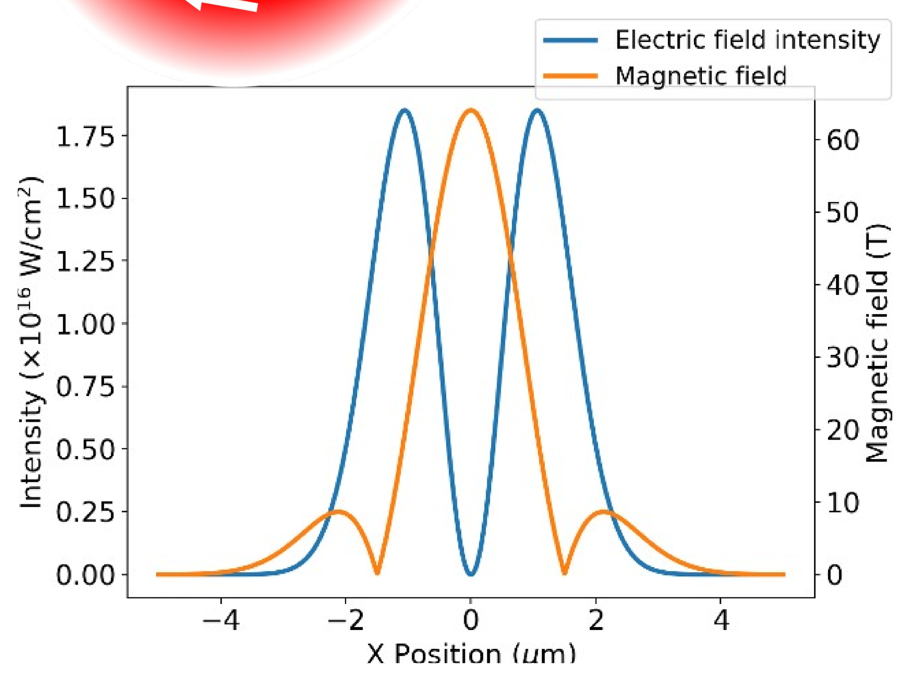
In this work, we perform Particle-In-Cell simulations, using OSIRIS[7-9], to optimize the spatial isolation of the magnetic field from the electric field by the interaction of AVBs with gold nanostructures. By the use of two circular apertured gold antennas, excited by two AVBs, we show the generation of ultrafast magnetic fields over 10's T-scale spatially isolated from the driving electric field, preventing the magnetic sample demagnetization. Our work paves the the route to the use of structured vector beams interacting with metallic antennas to allow pure magnetic interactions with matter at femtosecond time scales.

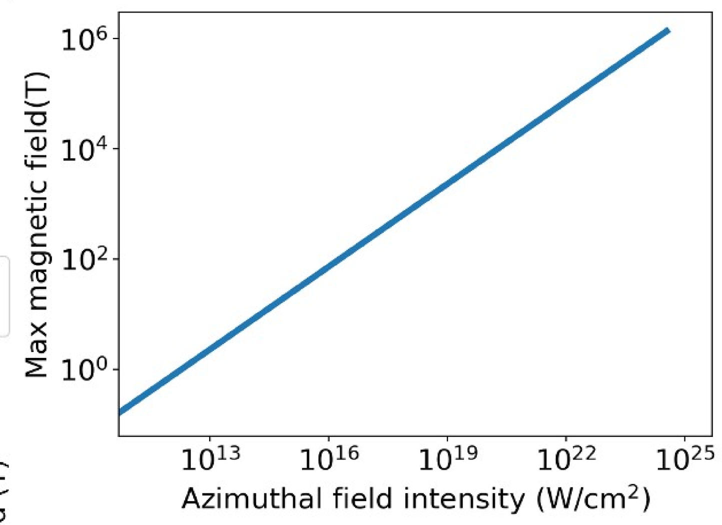
Azimuthal vector beams (AVBs)

$$\vec{E}(\vec{r}) = E_0 \frac{\rho}{w_0} e^{-\rho^2/w_0^2} \vec{u}_\phi$$

$$\vec{B}(\vec{r}) = -\frac{E_0}{c}\frac{\rho}{w_0} e^{-\frac{\rho^2}{w_0^2}} \vec{u}_\rho - 2\frac{E_0}{c}\frac{\lambda}{2\pi w_0}\left(1-\frac{\rho^2}{w_0^2}\right) e^{-\frac{\rho^2}{w_0^2}} e^{-\frac{\pi}{2}} \vec{u}_z$$



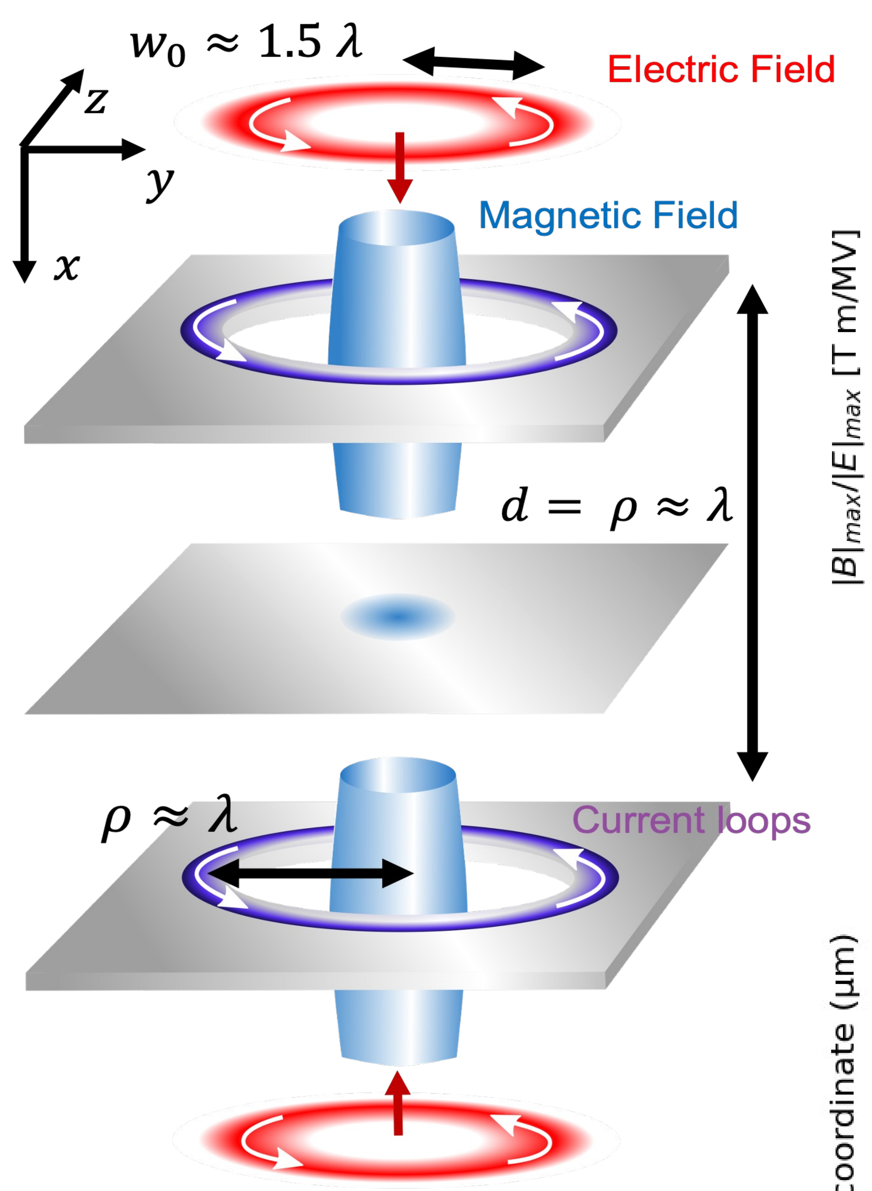




CoFeB demagnetization limit[10]:

$$E < 100\ \mathrm{MV/m}$$

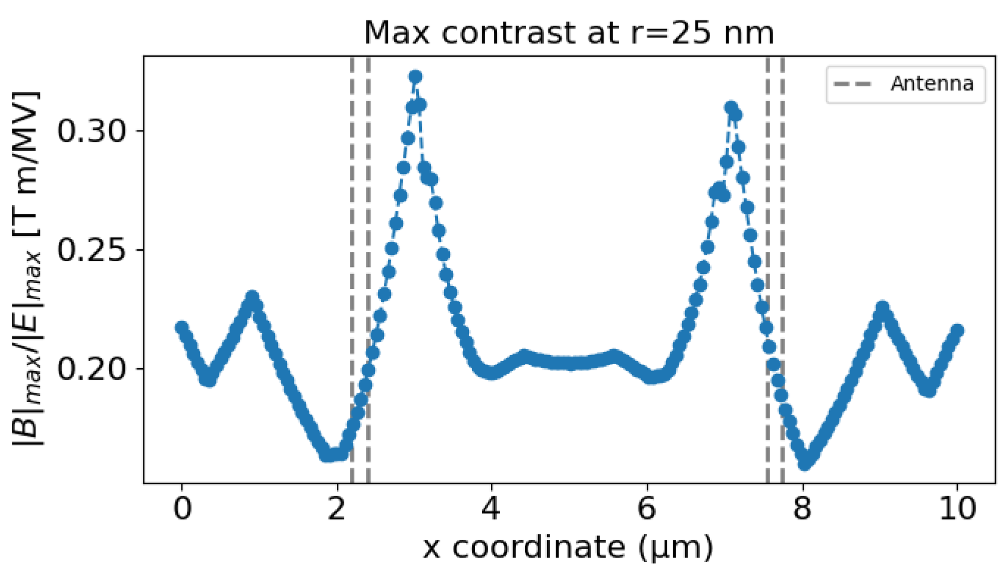
This constraint limits the maximum feasible magnetic field amplitude for pure magnetic interactions



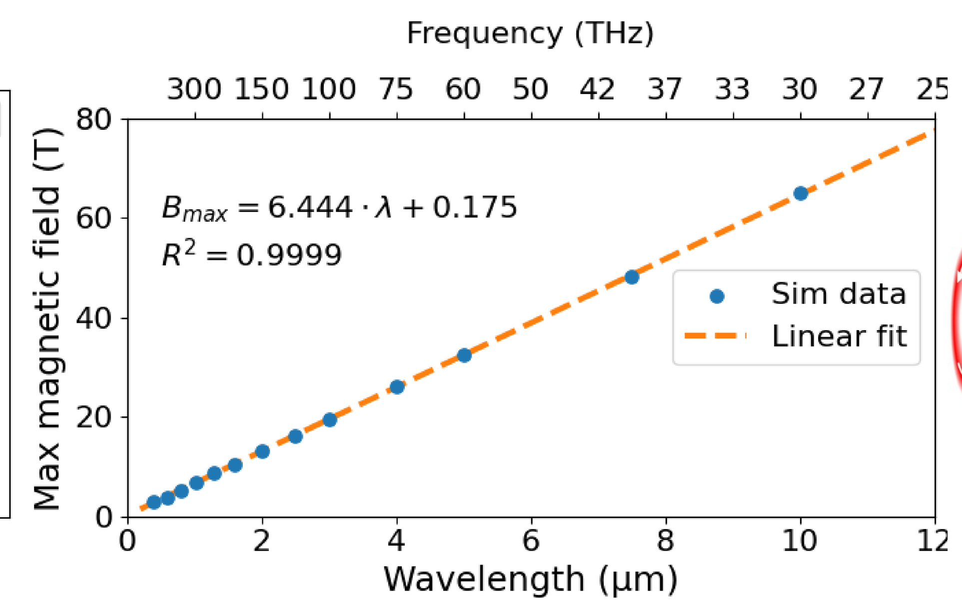
$E_0 = 14.5\ GV/m$ $\lambda = 5\ \mu m$

$\tau_{FWHM} \approx 16\ fs$ $f = 60\ THz$

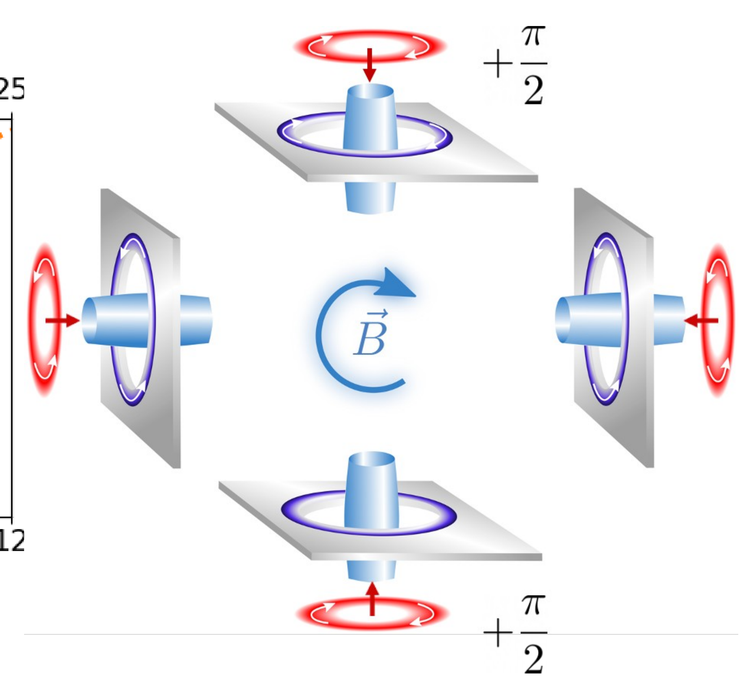
1. Ratio between magnetic and electric field at the sample edge



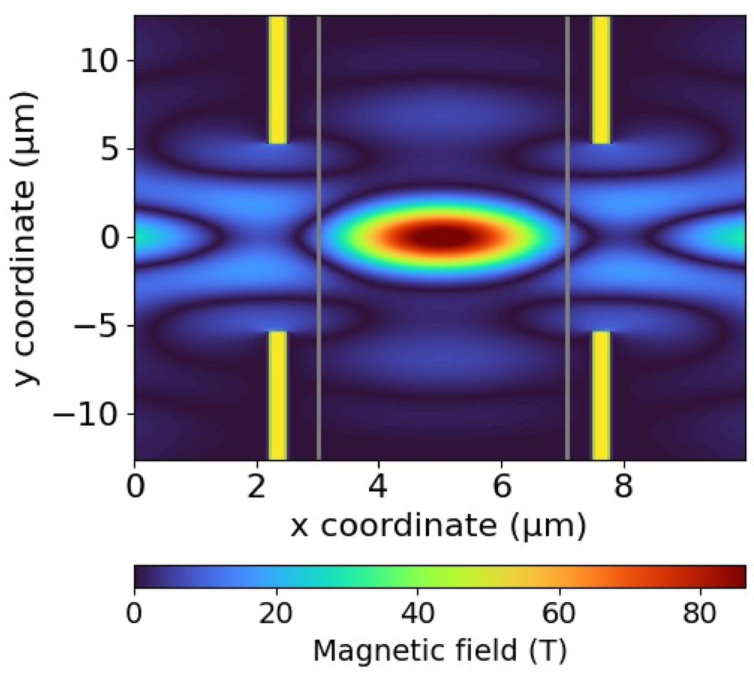
2. Wavelength dependence of the max magnetic field



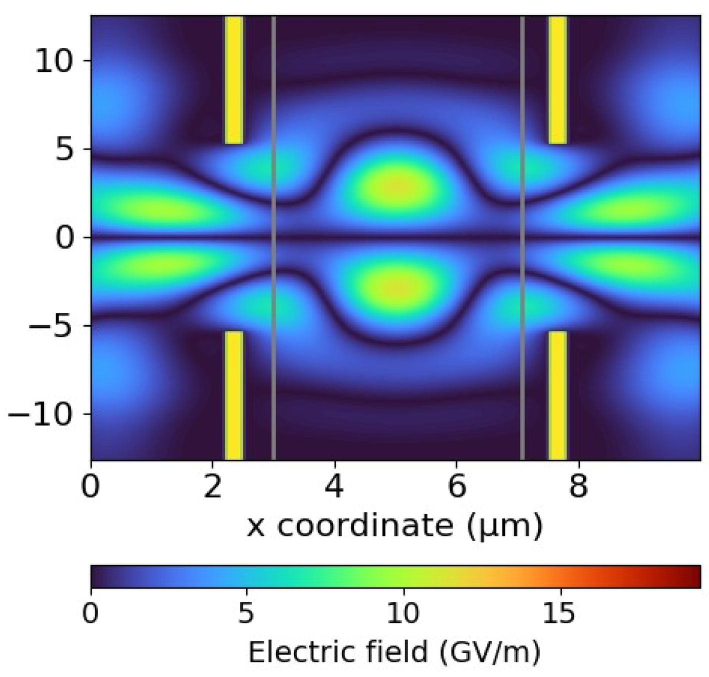
3. Proposal for circular polarization



Magnetic field



Electric field



- The AVBs induce fast oscillating current loops in the gold antennas surface.
- The current loops in each antenna generate a magnetic field needle distribution which propagates inside the cavity.
- At the magnetic sample edge (radius of 25 nm) ultra fast magnetic fields up to 30 T can be generated without sample demagnetization by the driving electric field.

Conclusions

1. Highly isolated ultrafast 10's T-scale magnetic fields can be generated from the interaction of structured laser beams and gold antennas
2. The maximum magnetic field amplitude exhibits a linear scaling with the driving wavelength (100's T for few THz laser pulses).
3. Circularly polarized magnetic fields with a crossed arrangement of the antennas.

References

[1] E. Beaurepaire, et al., Phys. Rev. Lett. 76 (1996), 4250.
[2] C. Hernández-García, et al., Optica 4 (2017), 520.
[3] K. Jana et al. Nature Photonics 15, 622 (2021)
[4] M. Blanco, et al., ACS Photonics 6 (2019), 38-42.
[5] L. Sánchez-Tejerina, et al. arXiv:2206.12238
[6] L. Sánchez-Tejerina, et al. In preparation.
[7] Fonseca R.A., et al., In P.M.A. Sloot et al. pp. 342-351 (2002).
[8] Fonseca R.A., et al., Plasma Phys. Controlled Fusion, 50, 124034 (2008).
[9] Fonseca R. A,. et al., Plasma Phys. Controlled Fusion, 55, 124011 (2013).
[10] S.Bonetti et al. Phys. Rev. Lett. 117 (2016), 087205.

Acknowledgments: This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation program (GrantAgreement No. 851201). We acknowledge support from Ministerio de Ciencia e Innovación (PID2019-106910GB-I00) and from Junta de Castilla y León FEDER funds (Project No. SA287P18). C.H.-G. acknowledges Ministerio de Ciencia, Innovación, y Universidades for a Ramón y Cajal contract (RYC-2017-22745), co-funded by theEuropean Social Fund.