Ultrafast acousto-magneto-plasmonics in hybrid metal-ferromagnet multilayer structures

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Nanostructured metal surfaces are presently used to effectively couple light to surface plasmons. This technology is also key to on-chip miniaturization of plasmonic sensors. We present a new plasmonic sensor, based on a tilted slit-groove interferometer, milled into a single noble metal film [1] or into a hybrid metal-ferromagnet structure [2]. Surface plasmons are excited at the groove and propagate towards the slit, where they interfere with incident light (Fig. 1). Due to the tilt angle the optical transmission through the slit shows a pronounced periodic interference pattern. A modulation of the complex surface plasmon wave vector results in a measurable change of the contrast and phase shift of the plasmonic interference pattern [1]. The wave vector of surface plasmons in our hybrid magneto-plasmonic gold-cobalt-gold system can be changed by switching in-plane magnetization using a weak external magnetic field (Fig. 1). Magneto-plasmonic modulation depth of up to 2% is achieved is this geometry. It can be further increased by covering the microinterferometer with high-index dielectric material [3].

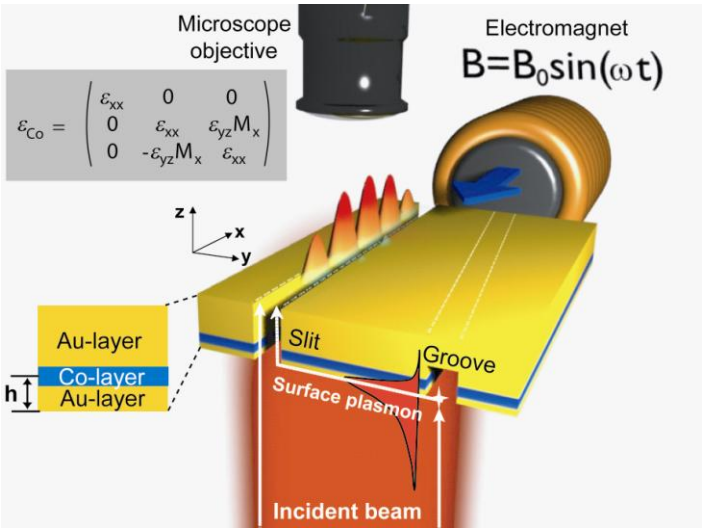

Fig. 1: Active magneto-plasmonic interferometry in tilted slit-groove interferometers patterned in Au/Co/Au multilayer structures. The magnetic field of an electromagnet switches the magnetization in a cobalt layer and thus changes the wave vector of a surface plasmon propagating between the slit and the groove, see Ref. [2] for details.

When combined with time-resolved optical pump-probe spectroscopy, femtosecond surface plasmon interferometry captures the dynamics of ultrafast electronic excitations and coherent lattice vibrations within δ_{skin}=13nm skin depth in gold with femtosecond time resolution [1]. Using a sapphire/cobalt/gold multilayer structure we generate ultrashort acoustic pulses by thermal expansion of a cobalt film impulsively heated by femtosecond laser pump pulses through sapphire substrate (Fig. 2a). The compressive acoustic pulse propagates through the gold layer at the speed of sound and is converted into a tensile pulse upon reflection from the gold-air interface. The wave vector of femtosecond surface plasmon probe pulses propagating along the gold-air interface serves as a sensitive probe to the local perturbations of the electron density within the skin depth δ_{skin}=13nm induced by the acoustic pulse. Varying the pump-probe delay time makes it possible to monitor the dynamics of acoustic reflection in the plasmonic pump-probe interferogram (Fig. 2c) and extract the pump induced modulation $\delta\varepsilon'+i\delta\varepsilon''$ of

surface dielectric function ε (Fig. 2d). On top of the slowly increasing thermal background due to the temperature rise of gold-air interface the apparent acoustic echo in $\delta\varepsilon'$ is observed indicating the change of surface plasmon wave vector $\delta k_{sp}=\delta\varepsilon'/2|\varepsilon|^2$. Straightforward mathematical analysis delivers the exponential shape of the acoustic strain pulse with the amplitude of ~10^{-4}. The 300 fs temporal resolution in our experiment is limited by the duration of femtosecond laser pulses and the roughness of the gold surface.

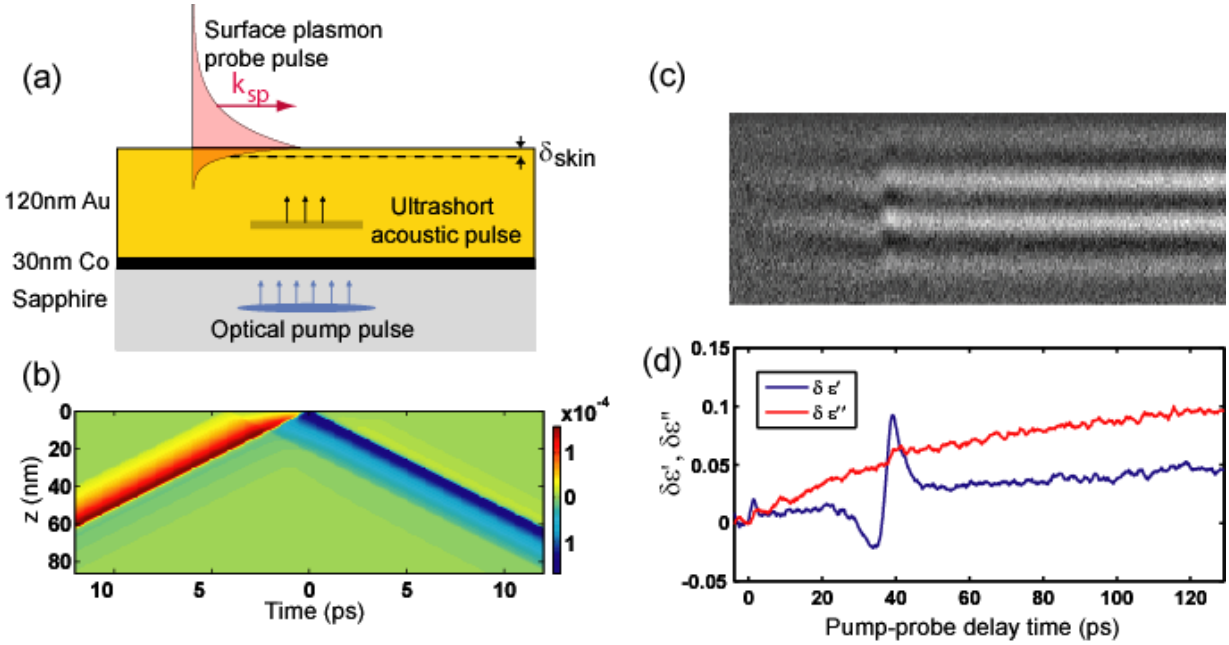

Fig.2: Femtosecond ultrasonics probed with ultrashort surface plasmon pulses. An ultrashort compressive acoustic pulse is generated by thermal expansion of fs-laser heated cobalt transducer and propagates through the gold film at the speed of sound (a). Upon reflection from gold-air interface the compressive acoustic pulse (layer with high electron density) is converted into the tensile pulse (layer with low electron density) (b). The dynamics of acoustic reflection is captured in a plasmonic pump-probe interferogram (c) and results into the pronounced modulation of the wave vector for a time-delayed femtosecond surface plasmon probe pulse (d).

Using much thinner cobalt transducers we were able to generate sub-picosecond acoustic pulses and use them to study the intrinsic ultrasonic attenuation of longitudinal phonons in gold in the THz frequency range. The observed surprisingly long mean free path of THz phonons in gold at room temperature opens the door to the nanometer resolved acoustic microscopy in metals and a new type of acoustic spectroscopy in solids with ultrahigh (μeV) spectral resolution over the entire Brillouin zone [4].

References

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