Phase-sensitive detection of ac inverse spin-orbit torques via spin pumping

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I will present data obtained with the first definitive ac measurements of both the inverse spin Hall effect (iSHE) and the inverse Rashba-Edelstein effect (iREE) in transition metal multilayers by use of the pure ac spin-currents generated in a metal at microwave frequencies via the mechanism of spin-pumping [1]. We utilized a phase-sensitive measurement technique that has been employed extensively in our laboratories for the past 15 years to characterize ferromagnetic resonance in spintronic alloys. The phase-sensitivity of the measurement methods allows us to unambiguously separate the three possible contributions to the measured ac voltage: iSHE (the inverse of damping-like spin-orbit torque) [2], iREE (the inverse of field-like spin-orbit torque) [3], and purely inductive signals due to Faraday's Law. Surprisingly, our measurements indicate that both the ac iSHE and iREE are comparable in scale for the Permalloy/Pt interface, and the iREE appears to be nonlocal, insofar as it is still detectable in a Py/Cu/Pt sample with 2 nm of Cu. This latter result is in agreement with recent reports of a nonlocal, dc REE when measured magneto-optically in the same kind of sample [4].

The more general implications of this result are three-fold. First, we can now directly test recently published theoretical predictions of giant ac spin currents. Such tests are essential to clarify our fundamental understanding of pure spin-currents, and to establish a more solid theoretical footing for potential spintronic applications, such as spin- and non-Boolean-logic. Second, the demonstrated measurement capability opens the door to the exploration of bandwidth limits for pure spin-current manipulation, which, to date, has only been studied at low frequencies of less than 1 kHz. Third, given that ac spin-current generation via spin-pumping is a linear effect, the resultant ac spin-currents are two orders of magnitude larger than their dc counterparts that stem from the nonlinear component of the gyromagnetic precession in the ferromagnetic source. Thus, there is now the opportunity to characterize spintronic phenomena with a much higher degree of measurement accuracy than can be achieved with methods that rely on nonlinear processes, which are far more difficult to unambiguously parameterize.

[1] M Weiler, et al., PRL 113, 157204 (2014).
[2] J. Jiao and G. E. W. Bauer, PRL 110, 217602 (2013).
[3] J. C. Rojas Sanchez, et al., Nat. Commun. 4, 2944 (2013).
[4] X. Fan, et al., Nat. Commun. 4, 1799 (2013).