Ultralow-current-density and bias-field-free spin-transfer nano-oscillator

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Supplementary Information

Note 1: Dependence of microwave properties on external magnetic field *H*

The external magnetic field is also found to influence the dynamical properties of the spin transfer nano-oscillators (STNOs). Fig. S1 shows typical microwave spectra for sample 1 at different in-plane fields *H* and for a fixed *I* = - 0.2 mA. We found that the output power achieved at zero field is the optimal value (this result is also valid for the other values of current (not shown)). When *H* increases from 0 to +100 Oe, the critical current to excite magnetization precession increases (not shown) and the oscillation frequency vs. field exhibits a blue shift, and is characterized by an out of plane oscillation axis *(S1)*. Similar results are achieved as *H* changes gradually from 0 to -100 Oe, with the only difference that the current range of persistent oscillations is reduced because the external field is added to the dipolar coupling from the polarizer, favoring the P configuration.

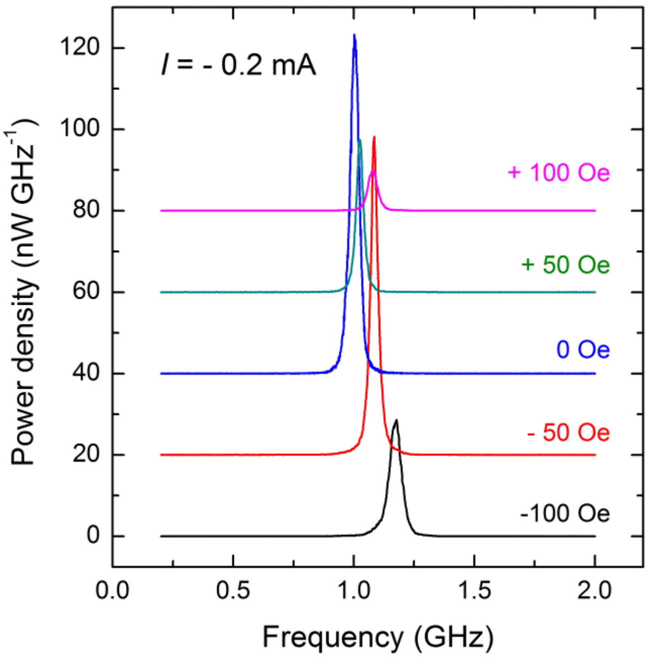

Figure S1: Microwave spectra as a function of external applied magnetic field at d.c. current bias *I* = - 0.2 mA for sample 1. The curves are offset by approximately 20 nW GHz^{-1} along the vertical axis for clarity. The positive /negative *H* favors antiparallel/parallel (AP/P) configuration between the fixed and free layers.

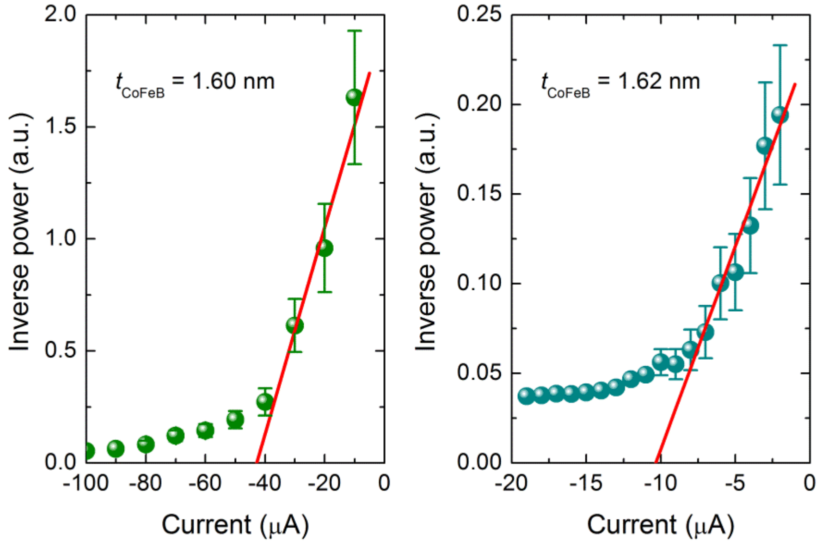

Figure S2: Dependence of the *inverse* normalized power on the current (dots: experiment, solid line: theoretical fit *(S2)* for sample 1 (left) and 2 (right).

Note 2: Critical current for microwave emission onset

The critical currents I_c for the onset of spin torque induced magnetization oscillations are computed by identifying deviations from a linear dependence for the *inverse* power on the bias current, *i.e.*, $(P_{exp}/I^2)^{-1} \propto (I_c\text{-}I)$*(S2)*. For sample 1 the I_c is ~ -45 μA, the corresponding current density J_c is -5.4×10^5A/cm^2, while for sample 2, the I_c value is ~ -10μA and J_c~ -1.2×10^5A/cm^2. These values are significantly smaller than in previous reports (*e.g.* 4.1×10^6A/cm^2*(S3)* and 1.2×10^6A/cm^2*(S4)*). To our knowledge, this is the first experimental evidence of such high oscillation power without bias field and with a critical current density below 6×10^5A/cm^2.

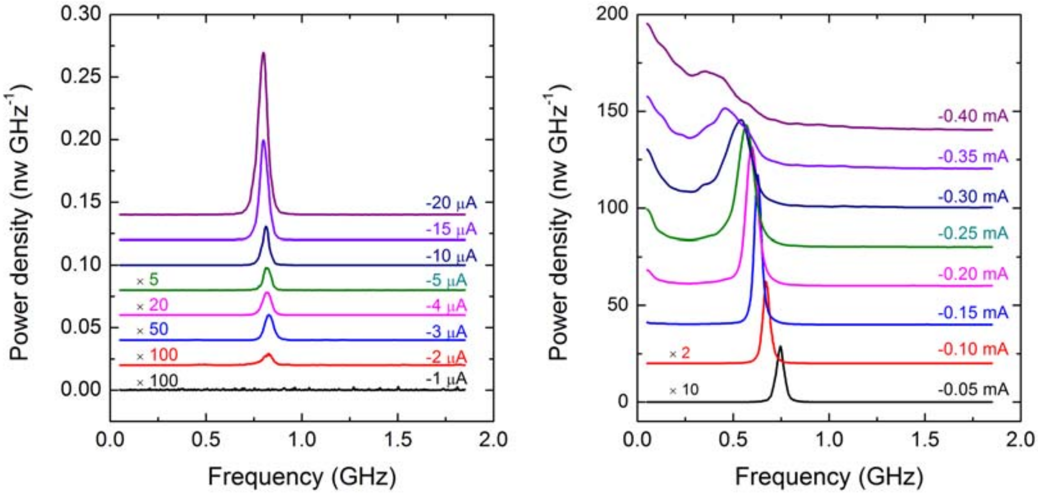

Figure S3: Microwave spectra as a function of d.c. current bias I at zero applied magnetic field for sample 2 (t_{CoFeB} = 1.62 nm). Left: low current bias regime. Right: high current bias regime. The curves are offset by approximately 0.02nW GHz^{-1} and 20 nW GHz^{-1} along the vertical axis for clarity for left and right respectively.

Note 3: Microwave spectra for sample 2

Figure S3 displays typical microwave spectra obtained for different values of I and for a device with t = 1.62 nm. At I = - 2 μA (the corresponding d.c. voltage V = - 1.2 mV) a pronounced peak is observed. This is the lowest value to observe high frequency microwave signal. When $|I|$> 0.15 mA, a low-frequency tail appears in the data. In the high current regime ($|I|$> 0.3mA) this complicated spectral behaviors indicate that the dynamics is non-uniform. In particular, a qualitative understanding can be seen from micromagnetic simulations at high currents where for some range of time the dynamics is switched off (see Fig. S4). We believe that the presence of this behavior could be the origin of these non-uniform dynamics. This scenario is similar to what has been observed in spin valve nanopillars (see Fig. 3 in ref. *S5*).

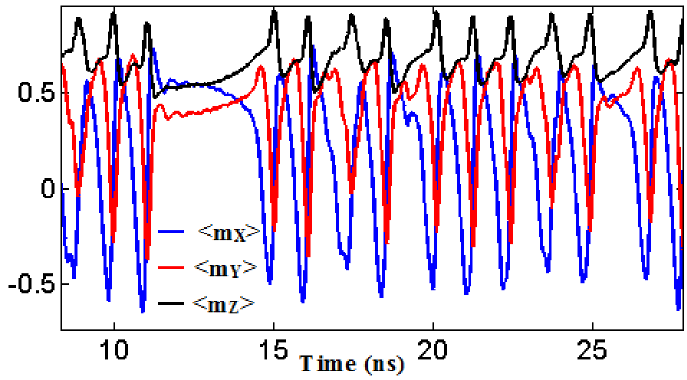

Figure S4: Micromagnetic time-domain traces of the average three components of the normalized magnetization driven by *I*= -0.33 mA for sample with *t*=1.62 nm. The other simulation parameters are the same as the ones used for the data in Fig. 4 of the main text.

Note 4: Effect of impedance mismatch

The power delivered to a load with impedance $Z_L = R_L + jX_L$ from a generator with impedance $Z_G = R_G + jX_G$ is given by *(S6)*

$$P_L = \frac{|V_G^2|}{2}\frac{R_L}{(R_L + R_G)^2 + (X_L + X_G)^2}, \quad \text{(E1)}$$

where V_G is the amplitude of the voltage generated by the microwave source. The maximum power is delivered to the load when X_L =$-X_G$ and $R_L = R_G$, *i.e.* when the impedances are conjugate-matched, in that case:

$$P_L^m = \frac{|V_G^2|}{8R_G}, \quad \text{(E2)}$$

For an STNO connected to an impedance Z_0, we have $R_L = Z_0 = 50\ \Omega$ and $X_L = 0$. Under the measurement conditions given in Fig. 1d for I = 0.3 mA, the measured MTJ resistance is R_G= 594 Ω, which results in $P_L^m/P_L > 3.5$ (we did not measure X_G, which also contributes to reflected power and therefore increases this number). Since P_L is 18 nW in this case, the maximum power that can be delivered to a matched load is $P_L^m > 63$ nW.

References

[S1]W. H. Rippard, M. R. Pufall, S. Kaka, T. J. Silva & S. E. Russek, *Phys. Rev. B* **70**, 100406 (R) (2004).

[S2] A. Slavin, &V. Tiberkevich, *IEEE Trans.Magn.***45**, 1875 (2009).

[S3] A. Deac, *et al., Nat. Phys.***4**, 803 (2008).

[S4] Z. M. Zeng, *et al., ACS Nano* **6**, 6115 (2012).

[S5] G. Finocchio, *et al., J. Appl. Phys.* **110**, 123913 (2011).

[S6] D. M. Pozar, *Microwave Engineering*, 2nd ed., Wiley, New York, 1998.