Nonlinear Characterization and Modeling of Magnetic Tunnel Junction (MTJ)-Based Magnetic Sensors

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As magnetic nanodevices (e.g., magnetic sensors) continue to shrink in size, the inherent nonlinear nature of magnetization dynamics may emerge during device operation. To optimize these devices and/or choose the most favorable operating point, one must first develop a characterization protocol tailored to nonlinear measurements in the presence of dynamic effects.

As these effects occur in the GHz range, i.e., ferromagnetic resonance (FMR) in nanoelements, their characterization would greatly benefit from advances in microwave measurement techniques. In particular, a comprehensive nonlinear analysis of magnetic sensors can be accomplished using a nonlinear vector network analyzer, which measures the incident and reflected waves’ ($A_1$ and $B_1$, respectively) magnitudes and phases at the excitation frequency and harmonic components to which energy may be transferred due to the device’s nonlinear characteristics.

The problem studied in this thesis is the identification of the new resonances at fractional frequencies of the free layer (FL) FMR mode resulting from the nonlinear nature of the spin-torque (ST)-induced magnetization dynamics. We discovered that all characterized magnetic sensors’ DC responses reveal peaks at frequencies that are the integer fractions (1/2, 1/3, 1/4, and 1/6) of the devices’ natural FL FMR frequency. These peaks, in turn, generate the second and third harmonics of $B_1$. New spectral lines at fractional frequencies of the devices’ FMR modes were observed using an alternative measurement technique, and the results of this study are also reported in this work.

A complimentary micromagnetic study showed that the experimentally observed DC response at frequencies that are the integer fractions of the FL’s resonant precession frequency can be defined by a low-order nonlinearity and strong magnetodipolar feedback between the magnetic layers adjacent to an MgO barrier. Additionally, the harmonic response is enhanced by the mutual ST effect between these layers.

Most importantly, strong magnetodipolar feedback permitted sub-harmonic injection locking within a wide range of integer fractions, which can be used in the development of a new generation of frequency multipliers.