NONLINEAR CHARACTERIZATION OF MAGNETIC READ SENSORS USING A NONLINEAR VECTOR NETWORK ANALYZER

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I. INTRODUCTION

A magnetic tunnel junction (MTJ) is the basis of modern magnetic read sensors commonly used in hard disk drives. Both the MTJ's tunnel magnetoresistance (TMR) and spin-torque (ST) effects exhibit a nonlinear bias-voltage dependence [1], [2]. These nonlinear dependences may be extracted through nonlinear analysis, which requires a tool suitable for high-frequency nonlinear characterization under various DC bias and AC power levels. Here, we present the exploratory Nonlinear Vector Network Analyzer (NVNA) measurements describing the MTJ's response at the excitation frequency as well as at harmonic components at which the energy may be present due to the MTJ's nonlinear characteristics. The NVNA measurements revealed a distinct harmonic response at certain frequencies, which are directly related to the MTJ's free layer (FL) ferromagnetic resonance (FMR) mode. Finally, these results can be used to determine the order of nonlinearity and its nature: electric *versus* magnetic.

II. NONLINEAR VECTOR NETWORK ANALYSIS

The NVNA measures the incident and reflected traveling waves (A_1 and B_1, respectively) at the excitation frequency (also known as the fundamental) and harmonic components [3]. In the present study, we measured 3 harmonics (fundamental, second, and third) for each excitation frequency. Due to the MTJ's nonlinear characteristics, the higher-order harmonics mix-down to DC thus additionally contributing to the DC response, which was measured simultaneously within the same NVNA run. The resultant second and third harmonics of B_1 were then counterposed to the DC response.

III. RESULTS

In Fig. 1, the DC response plotted for selected DC bias currents captures the change in the shape of the FL mode (peak *versus* dip) with respect to the direction of the DC bias current. At non-zero I_{DC}, the DC response exhibits a frequency-dependent characteristic, which may be associated with the predominant contribution of the second harmonic whose frequency dependence in turn is clearly seen in Fig. 2(a). Moreover, at non-zero I_{DC}, the DC response reveals peaks at lower frequencies than the FL FMR mode. Since they are located at frequencies that are the fractional ratios (1/2, 1/3, 1/4, and 1/6) of the MTJ's natural FL FMR frequency, they can be characterized as *sub-harmonics* of the FL mode. The theory of nonlinear oscillations suggests that the MTJ's inherent nonlinear characteristics may give rise to the oscillations of the FL's base natural frequency under the AC excitation signal with the frequency considerably lower (but still an integer ratio!) than the FL mode [4]. This would produce the DC response at sub-harmonics of the FL mode.

In Fig. 2, the second and third harmonics of B_1 indicate distinct peaks at multiples of the FL FMR mode's sub-harmonics corresponding to 1/2, 1/4, and 1/6 frequency of the FL. On the contrary, the FL mode and its sub-harmonic located at 1/3 the frequency of the FL *do not* produce their second and third harmonics, implying that even and odd sub-harmonics are attributed to different types of nonlinear characteristics, *e.g.*, electric *versus* magnetic. One such example are the harmonics of the magnetic read sensor's FL mode, which do not produce a measurable contribution to the FMR spectrum being caused by inhomogeneous magnetization oscillations [5].

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Our ongoing research is focused on verifying the suggested physical interpretation of the origin of sub-harmonics using micromagnetic modeling.

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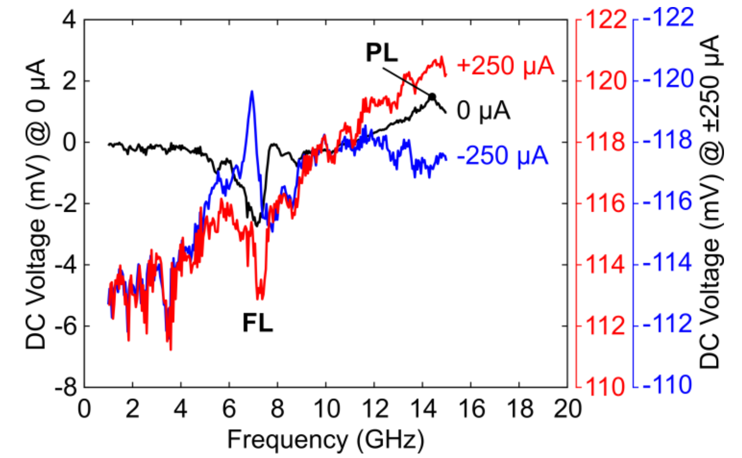

Fig. 1 DC response obtained with a Keysight N5247A and Keithley 2400 DC sourcemeter at –5 dBm source power level and selected DC current bias points. –5 dBm was chosen to emphasize the nonlinear phenomenon.

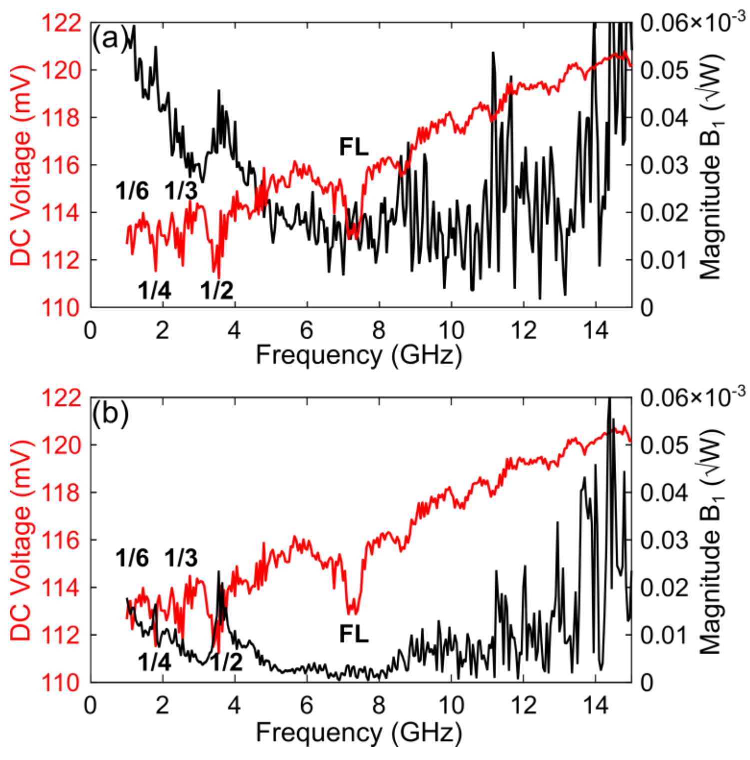

Fig. 2 NVNA measurements obtained with a Keysight N5247A at +250 μA DC current through the sensor, 15 Hz IFBW, and –5 dBm AC power. DC response as well as the (a) second and (b) third harmonics of B_1 plotted versus the excitation frequency.