**Spin torque diode with perpendicular anisotropy used for passive demodulation of FM digital signals.**

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Recent advances in the spintronic design and fabrication techniques have led to the development of spin torque diodes having a *perpendicular magnetic anisotropy* (STD-PMA) in their free layer. Such STD-PMAs can act as energy harvesters of ambient microwave radiation [1], and when driven with a dc bias current, can operate as microwave generators [2]. The analytical formalism [3] has shown that STD-PMAs have a number of interesting properties. In particular: (i) in the presence of an external microwave current they can produce a rectified dc voltage that is linearly proportional to the external microwave frequency, and independent of the input power; (ii) the STD-PMA can perform a signal rectification without an independent power supply, drawing power entirely from the input signal; (iii) in contrast with the traditional spin torque diodes, the STD-PMA do not require an external bias magnetic field, and therefore can be easily integrated with CMOS and other microelectronic systems; (iv) the power threshold of operation of STD-PMA is rather low (several nanowatts), and thus, they can be used in applications where non-spintronic (e.g. Schottky-diode-based) devices fail; (v) above a particular threshold frequency, the STD-PMA does not produce a dc voltage, thus acting as a natural lowpass filter. Here, we propose a novel application for an STD-PMA: this device can perform *passive demodulation* for low-power frequency-modulated (FM) signals. To demonstrate this effect we performed a numerical simulation for an STD-PMA under the action of an external FM signal. The magnetization dynamics of the STD-PMA free layer, which performs the signal demodulation, was modeled using the Landau-Lifshift-Gilbert-Slonczewski equation in a macrospin approximation. We chose the following typical parameters of the system. We used a 1.65 nm-thick circular free layer having a radius of 50 nm, and made of $Co_{20}Fe_{60}B_{20}$. With this configuration, the effective field of the 1st order PMA was 1162 mT, and the field of the 2nd order PMA was 63 mT. The Gilbert damping parameter was 0.02, the spin-polarization efficiency was chosen to be 0.6, and the pinned layer of the STD-PMA was assumed to have the in-plane magnetization. With these parameters, the static magnetization of the free layer had an equilibrium out-of-plane angle of 45 degrees, a resistance of $\approx 800\ \Omega$, and a tunneling magneto-resistance (TMR) of 112.5%. The two figures below demonstrate the numerically modeled STD-PMA performing both digital and analog FM demodulation. Fig. 1 shows the passive demodulation of a signal encoded with frequency shift keying (FSK). A short digital data sequence with a data rate of 2.5 MB is shown in Fig. 1(a), with voltages varying between a high and low state, and Fig. 1(b) shows this data encoded in the frequency of a signal, where $f_{in}$ = 40 MHz is representing the "low" state and $f_{in}$ = 60 MHz is representing the "high" state. The FSK signal has two powers, starting initially at 14 nW (-48dBm), increasing to 25 nW (-45 dBm), then again decreasing to 14 nW. When the FSK signal is incident on the simulated STD-PMA, it produces a dc voltage as shown in Fig 1(c). For the "low" state, the STD-PMA produces $V_{out}$ = 400 μV, and in the "high" state the STD-PMA produces $V_{out}$ = 600 μV. Note, that the voltage $V_{out}$ is only dependent on the input frequency, and is independent of the input power. It is also important to emphasize, that despite the low power levels of this signal, the STD-PMA is powered entirely by the external signal, and that the magnetic anisotropy allows its operation in the absence of a bias magnetic field. The FM demodulation of an analog signal using an STD-PMA is demonstrated in Fig. 2. An analog signal with frequencies scanning a 5 MHz bandwidth (Fig. 2(a)) is FM modulated by a 50 MHz carrier signal. The power spectral density (PSD) of the signal after a single-sideband FM modulation is shown in Fig. 2(b), with a bandwidth in the 50-60 MHz frequency range. The curve presented in Fig. 2(c) shows that the STD-PMA output dc voltage faithfully reproduces the shape of the input analog signal. In summary, a spin torque diode with perpendicular magnetic anisotropy can act as a reliable FM demodulator that does not require any power and/or any bias magnetic field. The basis of its operation is the linear relationship between the input frequency and the STD dc voltage output. Our numerical simulation has shown that an STD-PMA can demodulate both a digital signal encoded by FSK, and an analog signal with a single-sideband FM modulation. We believe, that STD-PMAs will be useful in power-critical applications, which has growing relevance for autonomous devices and internet of things (IOT) applications.

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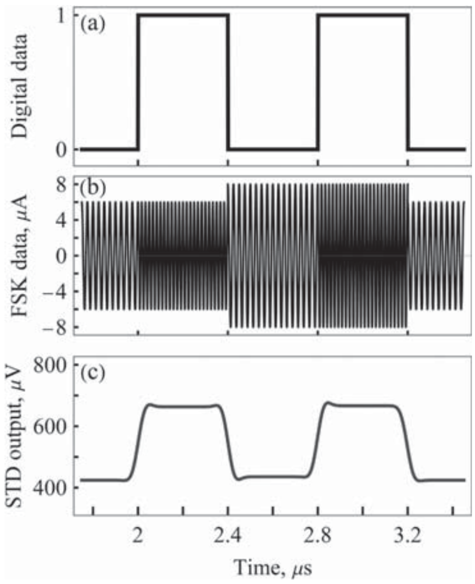


**Fig. 1. Demodulation of an FSK (digital) FM signal: (a) Input digital logic signal, where the "high" state indicates "1", and the "low" state indicates "0"; (b) The input logic signal encoded with FSK, where 60 MHz is "1", and 40 MHz is "0". Note, that the signal amplitude increases from 6 to 8 μA, a power change from 14 nW to 25 nW. (c) STD-PMA response to the FSK input, where 600 μV is "1" and 400 μV is "0". The signal is dependent only on the signal frequency and is independent of the signal amplitude.**


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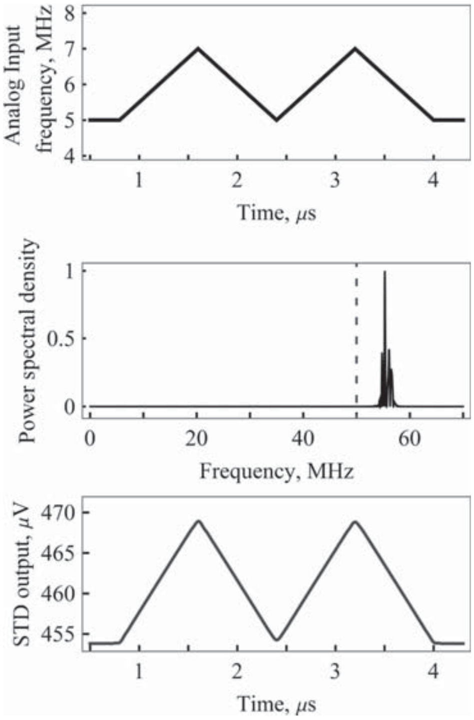


**Fig. 2. Demodulation of an analog FM signal: (a) Frequency of the analog signal. Signal has a bandwidth of 2 MHz; (b) Black line shows the power spectral density (PSD) of the analog signal after it was single-side-band FM modulated by a 50 MHz carrier frequency, shown by a dashed purple line; (c) Demodulated dc voltage output of the STD-PMA.**