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ANTENNA DEVELOPMENT FOR MULTIFUNCTIONAL ARMOR APPLICATIONS USING EMBEDDED SPIN-TORQUE NANO-OSCILLATOR (STNO) AS A MICROWAVE DETECTOR

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ABSTRACT

Recent advances in spintronics resulted in the development of a new class of radiation-resistant nano-sized microwave devices - spin-torque nano-oscillators (STNO). To use these novel nano-scale devices in wireless communications system as either microwave sources or detectors it is necessary to develop antennas coupled to STNO and providing efficient radiation and reception of microwave radiation. We demonstrate that it is possible to design antennas of a sub-wavelength size that have sufficiently high efficiency to be successfully used in spintronic communication devices. A coplanar antenna has the best performance characteristics, because its impedance could be easily matched with the impedance of nano-scale spintronic devices. We developed prototype spintronic devices with matched coplanar antennas (oscillators and radar detectors) which could be embedded into armor, thereby improving the survivability of the antennas as well as reducing the visual signature of antennas on military vehicles.

INTRODUCTION

The discovery of the spin-transfer-torque (STT) effect in magnetic multilayers, theoretically predicted by J. C. Slonczewski [1] and L. Berger [2] and after that experimentally observed by many authors [3–14], opened a possibility for a new method for the generation of microwave oscillations that does not involve any semiconductor materials or devices [15]. It has been predicted in [1-2] that direct electric current passing through a magnetized magnetic layered structure becomes spin-polarized, and, if the current density is sufficiently high, this spin-polarized current can transfer sufficient spin angular momentum between the magnetic layers to destabilize the static equilibrium orientation of magnetization in the thinner ("free") magnetic layer of a magnetic layered structure.

Depending on the actual geometry and properties of the magnetic layered structure and the magnitude of the external bias magnetic field, this phenomenon can lead either to the magnetization switching (reversal of the magnetization direction) [6, 16–19], or to the excitation of magnetization precession with the frequency close to the frequency of the ferromagnetic resonance (FMR) in the "free" magnetic layer [8–13]. In the last case the frequency of the current-induced precession depends on the current magnitude, and, typically, lies in the microwave range. The generated microwave signal can be registered as oscillations of the giant magnetoresistance (GMR) [3, 8, 20] or tunneling magnetoresistance (TMR) [21–23] due to the fact that in the course of precession the orientation of magnetization of the "free" layer relative to the static magnetization of the "fixed" layer oscillates with microwave frequency. Figure 1 shows schematically the magnetization precession in the "free" layer ($\bar{\boldsymbol{M}}_{free}$) with microwave frequency about an applied magnetic field ($\bar{\boldsymbol{H}}$).

Microwave STNO based on either the fully metallic GMR spin valves or magnetic tunnel junctions (MTJ) (which have a thin dielectric spacer between the magnetic layers and are based on the TMR effect), are very attractive for potential applications in active nano-sized devices in microwave spintronics [15, 25–33]. The major problem that arises during the development and application of such nano-sized devices is the small output power that can be extracted from a single STNO. In the case of a STNO based on the GMR effect this power is relatively small (around one nW) [8–9, 20], while in the case of a STNO based on the TMR effect it can reach 0.5 μW [21–24, 34].

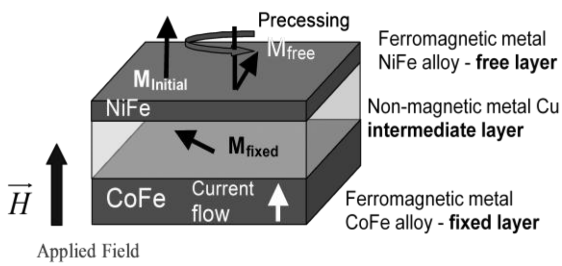

Figure 1. Precession of the free layer magnetization ($\bar{\boldsymbol{M}}_{free}$) with microwave frequency about an applied magnetic field ($\bar{\boldsymbol{H}}$) [13].

Figure 2 shows the STNO and the conventional electronic oscillator.

The typical level of operating microwave power of modern telecommunication devices is around 10 – 1000 μW. Thus, to create a practical source of microwave signals based on STNOs it would be necessary to use arrays of coupled and synchronized STNOs [34–36]. There are two approaches to create such an array of STNOs.

The first (traditional) approach is to form an array of *N* oscillators connected in parallel or in series and coupled by a common bias current. In such a case, as it was shown in [37], the output power extracted (through the magneto-resistance (MR) mechanism) from an array of *N* synchronized STNOs is *N* times larger than the power of a single STNO.

The second approach is to place *N* STNOs (coupled through their dipolar electromagnetic fields) inside a resonator with a high Q-factor and extract the power through the dipolar emission mechanism [24]. In this case, as it was shown in [38], the output power of the array of *N* oscillators can be N^2 times larger than the power of a single oscillator. This statement remains correct as long the total microwave power extracted from the resonator remains smaller then the power lost to Gilbert damping in a single STNO in the array [24].

In order to use either a single STNO or an oscillator array in telecommunication devices, it is necessary to have a coupling device, which would allow one either to effectively transmit the STNO-generated microwave signal to an outside transmission line, or to receive the external microwave signal (e.g. a signal from another STNO). This coupling device should have the impedance that is effectively matched to the impedance of a single STNO (or an STNO array). The simplest example of such a coupling device is a matched microwave antenna.

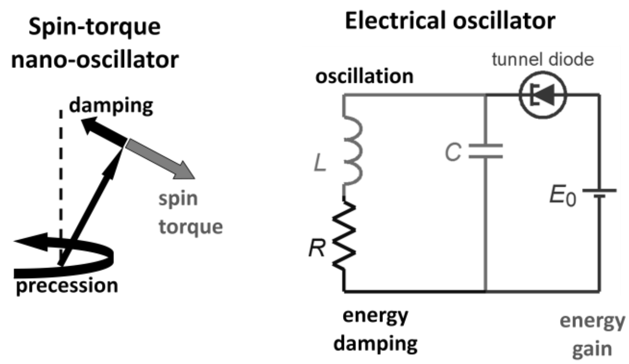

Figure 2. STNO and electrical oscillator [15].

DESIGN OF MICROWAVE ANTENNA SYSTEMS CONTAINING STNOs

In order to use either a single STNO or an STNO array as a voltage-controlled oscillator in future telecommunication systems it is necessary to have a coupling device, which would allow one either to effectively transmit the STNO-generated microwave signal to an outside transmission line, or to receive the external microwave signal (e.g. a signal from another STNO). This coupling device should effectively match the impedance of a single STNO (or an STNO array) with the impedance of a transmission line.

Current literature has a very limited number of papers available describing the synchronization of several STNOs. The first report on the synchronization of two STNOs based on magnetic nanocontacts was presented in [34]. A theory of mutual and forced synchronization of several STNOs [15, 36, 39–40] was developed soon after the first experimental publication. The main results of this theory were recently confirmed in the experiment where the synchronization of four vortex-based STNOs was investigated [35]. The above mentioned pioneering research uncovered several problems with the implementation of synchronized STNO arrays. One of the crucial limitations arising in the case when the STNOs in the array are coupled by a common bias current and MR mechanism is used to extract the power from the array is the fact that the total power of the array in this case is proportional to N (not to N^2) where N is the number of coupled STNOs [37–38].

This limitation forced us to examine other possible methods to extract the microwave power from an STNO array. The extraction of the microwave power from an array of synchronized STNOs is possible through the direct electro-magnetic radiation, and that method could be convenient and useful for the large arrays of oscillators [24]. Another problem arises from the fact that a typical impedance of a single STNO can vary from several Ohm to hundreds of kOhm. Therefore, the impedances of a STNOs or STNO array are not matched to the impedance of the free space $Z_0 = 120\pi \approx 377$ Ohm. This mismatch will create additional losses in the amount of radiated power. Yet another important problem is the conversion of a microwave signal generated by a single STNO (or an array of synchronized STNOs) into the form that is convenient for wireless communications. The efficiency of the standard method, based on the extraction of the microwave current from STNO (or STNO array) through the MR mechanism and the following excitation of an antenna by this current, is limited by the above mentioned impedance mismatch effect. At the same time, the microwave signal generated by a single STNO (or by an array of synchronized STNOs) can be transmitted/received through the natural dipole radiation, but the theory of these operations has not been developed yet.

We believe that there are two possible ways to solve the above described problems:

1. The development of an impedance-matched microwave antenna for STNOs or STNO arrays. This impedance-matched antenna will allow us to substantially improve the radiation characteristics of STNO-based auto-oscillators even in the case when the generated microwave current is extracted from STNO through the conventional MR mechanism.

2. The development of a passive planar microwave structure with embedded STNOs (or STNO arrays). This structure will function as a matched antenna, but, in contrast with the previous case, the microwave power will be extracted not through the MR mechanism, but through the direct electromagnetic radiation from the structure. For example, such a structure can comprise a microstrip resonator matched to a free space with embedded STNO or STNO array. Several examples of such structures are considered in [24].

Although, in principle, the second option [24] seems to be much more attractive than the first one (its practical realization is rather complicated, especially for large arrays of STNOs).

Therefore, we concentrated our efforts on the solution of the first problem – development of an optimal impedance-matched microwave antenna for STNOs or STNO arrays.

Our technical approach was to fabricate STNOs using planar micro- and nanotechnology [15, 33]. In order to extract the microwave power from these devices (typically, through the MR mechanism) they were embedded into a planar microwave system. In most cases this system is a coplanar waveguide (CPW) described in [27, 33]. The natural type of the impedance-matched antenna would be an antenna based on the similar planar technology. The main advantages of such a planar antenna are:

- Antenna and STNOs can be fabricated in the same technological process, therefore, the system will be technologically simple and more reliable;
- It is easy to impedance-match the antenna with the planar microwave system containing embedded STNOs (in some cases this system can be the antenna itself, i.e. the microwave planar system with STNOs functions as a matched antenna);
- The size of the antenna can vary in a wide range (can be longer or shorter than the wavelength of a microwave signal generated by a STNO or STNO array);
- Typically, planar antennas have smaller sizes than the non-planar antennas. Therefore, planar systems are convenient for the development of miniature microwave devices;
- Due to the use of the standard planar technology the resulting device (STNO + antenna) can be made sufficiently cheap to become practical;
- Planar antennas are convenient for experimental investigations of the systems with STNOs and for their applications in extreme environments, e.g. battlefield or outer space.

Taking into account the above described advantages of planar antennas we selected the design and possible applications of coplanar antenna. This planar antenna design has a two-layer structure:

- *Top layer* is a thin conductor that has a topology of the designed antenna (see Figure 3).
- *Bottom layer* which is a dielectric substrate.

The antennas that we considered had a simple two-layer structure, but some of the antenna designs have more than two layers.

We designed antennas for experiments involving STNOs by fixing the values of several parameters that were specific to samples and experimental setup [27]. We used the following values of the input parameters:

- Frequency range: 1÷6 GHz. The STNO samples used in our experiments had the operational frequency in that range [27].
- The experimental samples were fabricated on the Duroid 6002 dielectric substrates [60]. This type of dielectric has a relative dielectric constant $\varepsilon = 2.94 \pm 0.04$ [41–42]. For simplicity in our

calculations we used the average dielectric constant $\varepsilon = 2.96$.

- The thickness of the dielectric substrate in the planar structure was 1.2 mm.

In this work we used the CPW antenna. A coplanar line is a structure in which all the conductors supporting wave propagation are located on the same plane, i.e. generally the top of a dielectric substrate. A coplanar waveguide (CPW) is composed of a median metallic strip separated by two narrow slits from an infinite ground plane, as may be seen in Figure 3 below. The characteristic dimensions of a CPW are the central strip width and the width of the slots. The structure is symmetrical along a vertical plane running in the middle of the central strip [43].

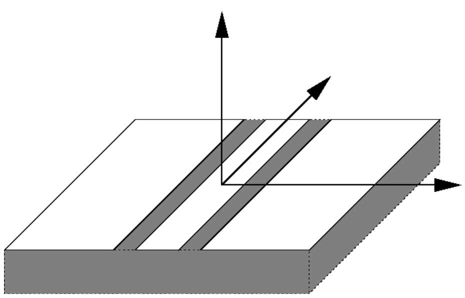

Figure 3. Coplanar waveguide line [43]. The top light filled layer is the area of metallization. The bottom layer is the dielectric. Duroid 6002 ($\varepsilon = 2.96$) was used in our experiments.

The CPW could be the most perspective antenna to work with STNO, because in real samples STNOs are embedded in the coplanar waveguides in order to simplify microwave signal extraction from each STNO.

EXPERIMENTAL RESULTS AND DISCUSSION

The device studied in our experiments was the STNO detector of microwave signals. It uses the spin-torque diode effect [21] for its operation. Microwaves are received by the CPW antenna. The microwave signals are passed into the magnetic tunneling junction (MTJ) of the detector. These microwaves cause the vector of magnetization of the free layer of the MTJ to precess. The resonance frequency of the free layer is controlled by an external bias magnetic field created by a tunable external magnet. As the orientation of the magnetization of the free layer relative to fixed layer changes, the generated resistance oscillates with time.

The MTJ microwave detectors with CPW antennas were fabricated by the research group of Prof. Krivorotov at the University of California in Irvine (UCI). The CPW antenna receives the microwave signal and transmits it to the input of the MTJ detector. The detectors were placed into enclosures made of brass and Duroid. A spintronics passive microwave MTJ detector with CPW antenna is shown Figure 4. The back of the MTJ was grounded to the enclosure. Through wire bonds, the MTJ microwave detector outputs a DC voltage to the SMA connector. In the interior of the case resides a permanent magnet attached to a set screw. Turning the set screw varies the magnetic field which changes the resonance frequency of the MTJ and the sensitivity of the spintronic microwave detector. Electrostatic discharge (ESD) diodes are also located inside the enclosure. A Duroid cover protects the internal components (removed for pictures). The enlarged view of the spintronics microwave detector with CPW is shown in Figure 5.

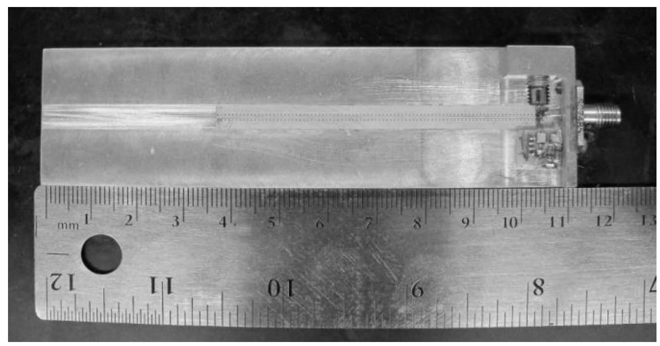

Figure 4. Spintronics passive microwave MTJ detector with coplanar waveguide antenna.

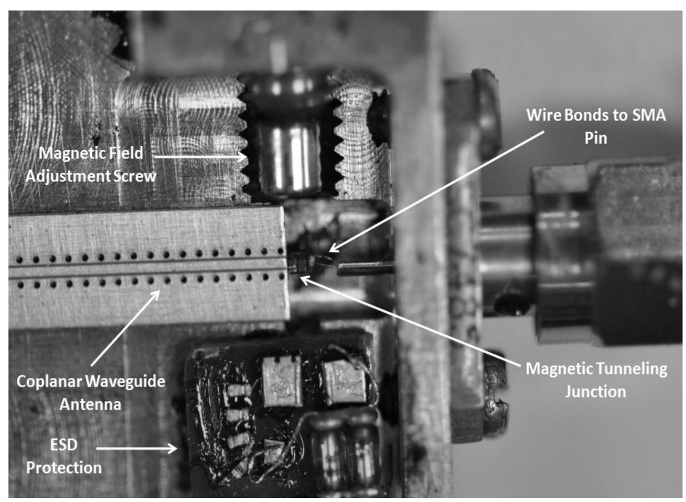

Figure 5. Enlarged view of the spintronics microwave MTJ detector with CPW antenna.

We were considering two major groups of passive STNO microwave detectors. The "A" group consisted of devices with in-plane precessing magnetic moment. The resonance frequencies of microwave detectors in "A" group were in the 4-6 GHz range.

The "B" group consisted of spintronic devices with out-of-plane precessing magnetic moment and the resonance frequencies in 1-3GHz range.

The characterization test of microwave spintronic detectors involved the following steps:

- 1 – 6 GHz initial scan to determine approximate resonance frequency
    - "A" group: focused scans at 4-6 GHz
    - "B" group: focused scans at 1-3 GHz
- Ten spintronic microwave detectors were tuned for maximum sensitivity. Turning the set screw from 0 to 3 turns at 1/2 turn increments tuned the magnetic field which changed the resonance frequency of the MTJ and the sensitivity of the detector.
- Multiple peaks were observed in some detectors sensitivity plots.
- "B" group devices typically had a higher voltage output (5B detector displayed the highest output voltage of approximately 6.5 mV)
- The absolute value of the extremum represents the voltage magnitude.
- Tuning the magnet on the "B" group detectors changed both the sensitivity and the resonance frequency. For the "A" group, it only changed the sensitivity.

The authors used a horn antenna to transmit the microwave frequency signal. The CPW antenna was used to receive this signal and apply it to the MTJ detector. Turning the set screw varied the magnetic field which changed the resonance frequency of the MTJ and the sensitivity of the spintronic microwave detector.

The plot showing the sensitivity of the MTJ spintronic detector # 2A with the in-plane precessing magnetic moment is shown in Figure 6. The plot showing the sensitivity of the MTJ spintronic detector # 5B with the out-of-plane precessing magnetic moment is shown in Figure 7.

As we can see from the comparison of plots in Figure 6 and 7, the voltage plot in Figure 7 has the higher maximum value $(>6$ mV). The out-of-plane precessing magnetic moment might be responsible for large detector efficiencies observed in our experiments with MTJ detectors and CPW antennas.

Our preliminary experimental results presented in figures 6 and 7 have demonstrated that spin-torque microwave detectors coupled to CPW antennas are capable of receiving external microwave signals in a laboratory experiment performed in the anechoic chamber developed at the TARDEC's Sensor Enhanced Armor and NDE laboratory.

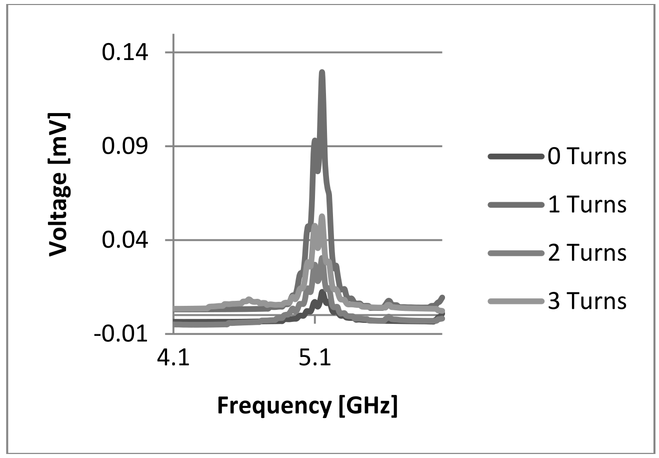

Figure 6. The plot showing the sensitivity of the MTJ spintronic detector # 2A with the in-plane precessing magnetic moment.

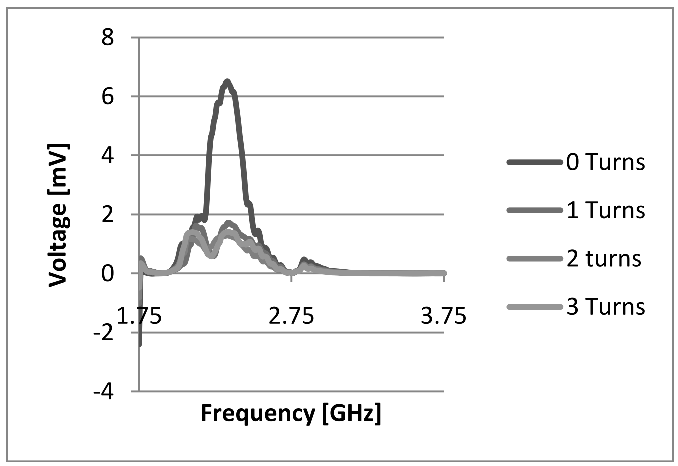

Figure 7. The plot of the sensitivity of the MTJ spintronic detector # 5B with the out-of-plane precessing magnetic moment.

The next step in the development of these novel detectors is the integration of those into protective surfaces of ground vehicles. The authors have begun the preliminary measurements of the effects of various protective materials on the MTJ detector with CPW antenna. Two types of materials: Alumina and silicon carbide (SiC) were placed between the transmitting horn antenna and the receiving CPW antenna and the signal strength was measured. The detector plots are shown in Figure 8. More work towards system integration is planned.

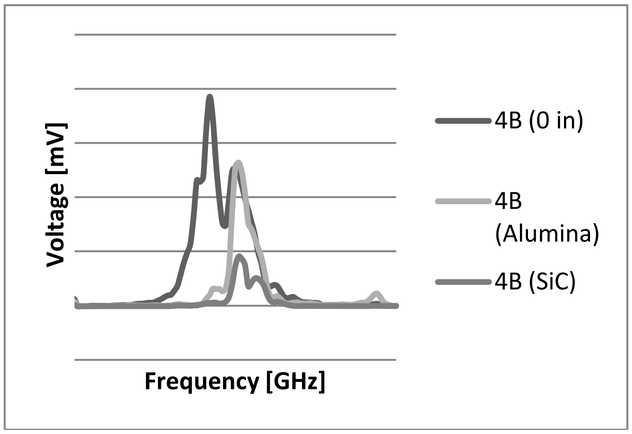

Figure 8. The effects of Alumina and SiC on the performance of the MTJ detector with CPW antenna.

CONCLUSION

We have demonstrated experimentally that nano-scale passive spintronic detectors of microwave radiation based on the spin-torque diode effect in MTJ and coupled to the sub-wavelength-size coplanar waveguide antenna are capable of receiving external microwave signals and can be used for the effective detection of external radar signals (see Figs.6,7) We have determined that the sub-wavelength-size antennas of the coplanar waveguide type are the most efficient for coupling the electromagnetic signals to spintronic detectors. We also have demonstrated that the performance characteristics of the spintronic detectors are strongly dependent on the material surrounding the device (see Figure 8). This effect should be taken into account when integration of spintronic detectors in the protective surfaces of ground vehicles is performed.

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