Ultra-fast artificial neuron: generation of picosecond-duration spikes in a current-driven antiferromagnetic auto-oscillator

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We demonstrate analytically and numerically, that a thin film of an antiferromagnetic (AFM) material, having biaxial magnetic anisotropy and being driven by an external spin-transfer torque signal, can be used for the generation of ultra-short "Dirac-delta-like" spikes. The duration of the generated spikes is several picoseconds for typical AFM materials, and is determined by the in-plane magnetic anisotropy and the effective damping of the AFM material. The generated output signal can consist of a single spike or a discrete group of spikes ("bursting"), which depends on the repetition (clock) rate, amplitude and shape of the external control signal. The spike generation occurs only when the amplitude of the control signal exceeds a certain threshold, similar to the action of a biological neuron in response to an external stimulus. The "threshold" behavior of the proposed AFM spike generator makes possible its application not only in the traditional microwave signal processing, but also in the future neuromorphic signal processing circuits working at clock frequencies of tens of gigahertz.

Generators of short in the time domain “Dirac-delta-like” pulses are widely used in modern electronics and optics. The most obvious applications of such generators are for the formation of trigger sequences, pulse-density modulation (PDM) of signals, and other signal processing purposes. In PDM the amplitude of an analog input signal is encoded by the relative repetition rate of the generated pulses. A train of “Dirac-delta-like” pulses with a constant repetition rate forms a Fourier image of equidistant sharp peaks in the frequency domain, which is known as a frequency “comb”. Generators of frequency-“combs” are used for dense frequency-division multiplexing (DFDM) in electronics, and dense linewidth-division multiplexing (DLDM) in optics to exploit the full bandwidth of the data transmission lines. In this approach, the generator frequencies can be locked to a corresponding frequency of the “comb”. Thus, one of the key characteristics of signal processing devices using the “comb” generators is the bandwidth of the frequency-“comb” generator, which is limited by the duration of a single pulse.

A similar type of pulse-encoded signals is used in nervous systems of biological objects, where response of a neuron to an input stimulus is a single spike, or a train of spikes with a certain sequence frequency, which is called an action potential in the cell biology. Therefore, the modern concepts of neuromorphic computing and signal processing include spike generators as a mandatory element of their architecture. Another peculiarity of a nervous system is the neuron’s threshold behavior, in a sense, that a neuron generates a response only when the

input stimulus is above a certain critical value (threshold). This nonlinear response is also a key feature for the operation of artificial neuromorphic devices.

Electronic frequency-"comb" generators, usually, employ the modern CMOS technology, and can have a compact design, but operate at relatively low frequencies, and, therefore, have a relatively low frequency bandwidth (< 50GHz). The optical comb generators offering microwave frequency spacing, based on the phase modulation in Fabry-Perot cavities, multi-frequency lasers, Brillouin-enhanced fiber lasers and phase modulation within an amplified fiber loop, can have a substantially wider frequency span (> 100GHz), but are rather complex devices, incompatible with the existing on-chip technology.

Spin-torque nano-oscillators (STNO) and spin-Hall oscillators (SHO) based on ferromagnetic (FM) materials are of a high interest for modern spintronics as tunable nano-scale generators of microwave signals, and, in principle, can be used as pulse generators, but their typical response time is determined by the frequency of the ferromagnetic resonance, and is limited to hundreds of picoseconds by the practically achievable magnitudes of the local bias magnetic field.

Recently, however, it has been proposed to use AFM materials as active layers of SHOs due to their ability to operate at higher frequencies, up to the THz range. In an AFM-based SHO, the spin current $j_{\text{spin}}$ created by the spin-Hall effect (SHE) in the adjacent heavy metal layer traversed by a direct electric current, induces a torque on the Neel vector of the AFM. If the spin...
polarization $p$ of the driving current in AFM is perpendicular to the equilibrium orientation of the Neel vector $k_0$, the Neel vector starts to rotate in the plane perpendicular to the vector $p$.\cite{14, 18, 19).

The extraction of an ac signal by inverse SHE (ISHE) in the adjacent layer of a heavy metal is, however, non-trivial, because it requires the motion of the Neel vector that is non-uniform in time. Several approaches were proposed to solve this problem.\cite{15, 18, 19}. For instance, it was shown in Ref.\cite{18}, that a non-uniform rotation of the Neel vector can be achieved in AFM materials with bi-axial type of anisotropy (e.g., NiO), where additional in-plane anisotropy creates an effective potential profile for the rotating Neel vector. The output signal of the AFM generators based on this mechanism, is however, a simple harmonic (sinusoidal) oscillation.

Here, we propose a design of an AFM-based spin-Hall auto-oscillator, capable of generating controlled sequences of ultrashort pulses with a typical pulse duration of a few picoseconds. The proposed generator is based on a layered structure consisting of a current-driven layer of a normal metal (NM) with a strong spin orbit-coupling, and an antiferromagnetic (AFM) layer with a biaxial magnetic anisotropy. Spin current ($j^{\mu \nu}$) created by the spin-Hall effect (SHE) in the NM and flowing into a thin AFM film creates a torque on the sublattice magnetizations of the AFM, which leads to a rapid switch of their orientation. This switch, in its turn, creates a short pulse of the spin current flowing back to the NM layer ($j^{\nu \mu}$), where it can be converted into an electrical signal by the inverse spin-Hall effect (ISHE), see Fig. 1.

The minimum duration of a short pulse is limited by a characteristic time of the current-induced AFM sublattice reorientation process. For a relative strong magnetic damping, this reorientation time is proportional to the effective Gilbert damping constant and inversely proportional to the magnitude of the in-plane magnetic anisotropy field in the AFM material (see Eq. (2) below). Since the effective Gilbert damping constant in sandwiched AFM/NM structures is mostly determined by the spin-pumping\cite{20}, it can be controlled, and the achievable reorientation time can be of the order of several picoseconds for typical AFM/NM bilayers, such as nickel oxide (NiO) and Pt. The pulse repetition rate in the proposed generator of ultrashort pulses can be easily defined, we assume that the angle $\phi$ is measured from the easy axis of the AFM\cite{18}. To make everything well-defined, we assume that the angle $\phi$ is measured from the easy axis $n_e$ ($\mathbf{n}_e = \cos \phi$). In terms of the angle $\phi$ the equation for the Neel vector dynamics has the following form\cite{18}:

$$\frac{1}{\omega_{ex}} \ddot{\phi} + \alpha_{eff} \dot{\phi} + \frac{\omega_e}{2} \sin 2\phi = \sigma j_e(t), \quad (1)$$

where $\omega_{ex} = \gamma H_{ex}$ is the exchange frequency and $\omega_e = \gamma H_e$. The term in the right-hand-side part of Eq. (1) describes the spin torque created by the electrical current $j_e(t)$ flowing in NM layer (expressed in the frequency range $\omega_e$).
The effective damping parameter $\alpha_{\text{eff}} = \alpha_0 + \alpha_{SP}$ includes both the intrinsic Gilbert damping constant $\alpha_0$ and the additional magnetic losses due to the spin pumping from the adjacent layer of the normal metal $\alpha_{SP}$. The losses due to the spin pumping depend on the thickness $d_{\text{AFM}}$ of the AFM layer ($\alpha_{SP} \sim 1/d_{\text{AFM}}$), and, therefore, can be adjusted in a certain range by a proper design of the geometric parameters of the AFM SHO.

The first term in Eq. (1) describes the inertial properties of an AFM SHO. However, when the damping is high ($2\alpha_{\text{eff}} > \pi \sigma j_{e}/(\sqrt{\omega_{e}\omega_{ac}})$) this term can be neglected in a qualitative analysis. It is really remarkable, that the spin dynamics of an AFM oscillator described by Eq. (1) is mathematically analogous to the dynamics of an overdamped physical pendulum in a gravitational potential under the action of an external torque $\sigma j_{e}(t)$. In this analogy the the magnetic anisotropy in the AFM layer plays the role of a gravitational field $g$, Gilbert damping plays the role of a friction, and the inverse of the exchange frequency plays the role of the pendulum inertial mass. Since the gravity is a directional field and the magnetic anisotropy is bi-directional, to make the full analogy we have to replace the angle of the Neel vector $\psi$ with the angle of the pendulum $\psi$ as $2\phi = \psi$, see Fig. 2(a). In the absence of the external torque $j_{e} = 0$ the "AFM pendulum" is in a ground state, which defines the energy minimum $\psi = \phi = 0$. A small, steady in time driving torque lifts the "pendulum" to a tilt angle $\psi_0 = \arcsin(2\sigma j_{e}/\omega_{e})$. This happens when the dc current $j_{e}$ is flowing in the NM layer $j_{e} = j_{dc} = \text{const}$. The maximum value of the tilt angle at a stationary state of the pendulum is $\psi_0^{\text{max}} = \pi/2$, because at this angle the returning torque from the "gravity" potential is maximized, and, if the torque overcomes this threshold $\sigma j_{dc} > \sigma j_{dc}^{th} = \omega_{e}/2$, the pendulum undergoes an infinite rotational motion [18].

Now, let us consider the dynamics of the pendulum when some additional torque $\sigma j_{t}$ is applied for a short period of time. In the initial situation the pendulum remains tilted with an angle $\phi_0$. After an additional torque $j_{t}$ is turned on, the angle $\phi$ starts to increase. If $j_{dc} + j_{t} > j_{dc}^{th}$, the pendulum overcomes the threshold angle $\psi > \pi/2$. At this point the torque created by the $j_{dc}$ alone is sufficient to continue the rotation of the pendulum, and, therefore, one could turn off the additional current $j_{t}$. Importantly, when $\psi > \pi$ the returning force, coming from the "gravitational" (or anisotropy) potential, is now assisting the torque $j_{dc}$, which results in a very fast acceleration of the pendulum in the region $\pi < \psi < 2\pi$. If the damping is sufficiently large to stop the infinite rotation ($2\alpha_{\text{eff}} > \pi \sigma j_{dc}/(\sqrt{\omega_{e}\omega_{ac}})$), the pendulum will relax to a new stationary point $\phi_0 + 2\pi$, which corresponds to the switching of the magnetization sublattices $M_1$ and $M_2$ to an opposite direction. Note, that we are interested in the case of relatively small values of the control current $j_{t}$, that requires the bias current $j_{dc}$ to be close to the threshold value ($j_{dc} \approx j_{dc}^{th}$), and the value of the effective damping in the AFM material to be rather large $4\alpha_{\text{eff}} > \pi \sqrt{\omega_{e}/\omega_{ac}}$.

The electrical field in the NM layer, produced by the back spin-pumping through the ISHE, is proportional to the angular velocity of the Neel vector: $E = \kappa \dot{\phi}$. The pendulum reaches maximum velocity $\phi_{\text{max}}$ (which deter-
The Neel vector rotates through the angle during one rotation) times per one period of the driving signal and the AFM material: \( j_{dc} \) - the amplitude of the dc component of the applied current, \( j_{ac} \) - the amplitude and frequency of the ac component of the applied current, and the effective damping constant \( \alpha_{eff} \) of the AFM material. In our numerical simulations we assumed a Pt NM layer and the AFM layer made of NiO. We took all the material parameters from Ref. [18], except for the \( \alpha_{eff} \).

The examples of the input and output signals of the proposed AFM spike generator are shown on Fig. 3. Fig. 3(a) shows the input driving current with a dc component fixed below the threshold \( j_{dc} < j_{dc}^{th} \). At the low values of the ac current amplitude \( j_{ac} \) the generator does not produce a significant output signal (Fig. 3(b)). With the increase of the \( j_{ac} \), at some point when the combined amplitude exceeds a generation threshold \( j_{dc} + j_{ac} = j_{ac}^{th} \), the device generates a single sharp spike of a significant amplitude during each period of applied ac current (Fig. 3(c), i.e., a periodic sequence of spikes (or a temporal "comb") is generated. For the parameters used in our numerical simulation (see Fig. 3) the duration of the numerically simulated spike \( \Delta t = 2.4 \text{ps} \) is close to the value analytically estimated using Eq. (2). The spike generation has a well-defined threshold on \( j_{ac} \), which is similar to the response of a biological neuron to an external stimulus, and the shape of the spike produced by the AFM generator also replicates a typical shape of a spike produced by a biological neuron [1]. With the further increase of the amplitude of the ac current above the threshold, the Neel vector could switch two (2\( \pi \) rotation) or more (\( \pi \) rotation) times per one period of the driving ac current (see Fig. 3(d)). Such a behavior is known for biological neurons as "bursting" [3]. The generation of "bursts" with a desired number \( n \) of spikes, however,
requires a fine tuning of the ac amplitude, because the
range of the required ac current amplitude \( j_{ac} \) rapidly
decreases with the increase of \( n \). Thus, below we catego-
erize the reactions of our artificial AFM "neuron" to
the external "stimulus" into "no spikes", "single spike",
or "bursting" regimes, independently of the number of
spikes generated in a "burst" (see Fig. 1).

The "phase diagrams" of the spike generation regimes
in an AFM auto-oscillator driven by a combined (dc +
ac) control signal are shown on Fig. 4 (a), (b). Two
"phase diagrams" are presented: the "phase diagram"
on the plane \( j_{ac}/j_{dc}^{th} \) vs. \( j_{dc}/j_{dc}^{th} \) at the fixed values of
the driving ac frequency \( f_{ac} = 20 \text{ GHz} \) and the AFM
material damping \( \alpha_{eff} = 0.01 \) (see Fig. 4 (a)), and the
"phase diagram" on the plane \( f_{ac} \) vs. \( \alpha_{eff} \) at the fixed values of
\( j_{dc}/j_{dc}^{th} = 0.8 \) and \( j_{ac}/j_{dc}^{th} = 0.3 \) (see Fig. 4 (b)).

As one can see from Fig. 4 (a) the threshold for the
spike sequence generation \( j_{ac} = j_{1}^{th} \) lays above the line
\( j_{ac} + j_{dc} = j_{dc}^{th} \), because the applied ac current, after over-
coming the potential barrier caused by the perpendicu-
lar anisotropy in the AFM "easy" plane, must produce a
sufficient work against the effective damping (see Fig. 2).
The work produced by the ac current depends on the
duration of its action, and, therefore, on the ac current
frequency \( f_{ac} \). Consequently, at the fixed value of the
dc current \( j_{dc} < j_{dc}^{th} \) the maximum ac current frequency
\( f_{ac} = f_{1}^{th} \), at which the generation of the spike sequences is
still possible, decreases with the increase of the effec-
tive damping \( \alpha_{eff} \) of the AFM material (see Fig. 4 (b)). We would like to note, that the effective damping
\( \alpha_{eff} \) can be adjusted not only by choosing a different
AFM material having a different intrinsic damping \( \alpha_0 \),
but also by changing the thickness of the AFM layer, as
the spin-pumping-related part of the effective damping is
inversely proportional to the AFM later thickness.

Note, that the maximum "clock" frequency of spike
generation in the proposed artificial AFM "neuron" de-
creases with the increase of the effective damping, and
is ultimately limited by the inverse duration of a sin-
gle spike determined by Eq. 2. Our numerical simula-
tions also show that this frequency can be increased up
to \( f_{ac} > 150 \text{ GHz} \) by the increase of the bias dc current
\( (j_{dc} \approx j_{dc}^{th}) \) in a narrow range of the \( \alpha_{eff} \) values.

A continuous generation of ultra-short pulses with a
random initial phase is also possible in the absence of
driving ac current by applying dc bias current with low
supercriticality \( 0 \leq \frac{(j_{dc} - j_{dc}^{th})}{j_{dc}^{th}} \leq 1 \), see right bot-
tom corner in Fig. 4 (a). The frequency of the pulse
train in this case rapidly increases with the value of dc
current[18] as \( f \approx \sqrt{j_{dc} - j_{dc}^{th}} \) and is not stable under the
fluctuations of the dc bias. However, such regime of
the spikes generation can be phase-locked by the injection
of ac control signal, which is indicated by the bending of
the single-spike phase for small values of \( j_{ac} \) in Fig. 4 (a).
This effect to be considered in detail elsewhere.

The application of the proposed AFM generator of
ultrashort spikes for traditional signal processing pur-
poses, for example, as a spintronic frequency multiplexer,
is also possible, and it requires a sufficiently wide fre-
quency bandwidth of the generated signal. The simu-
lated spectral density of a spike sequence generated by
the above described AFM auto-oscillator at the ac driv-
ing frequency of \( f_{ac} = 15 \text{ GHz} \) is shown on Fig. 5. The
spectrum represents a well-known frequency "comb" with
a slow decay of the amplitude of higher harmonics with
the increase of the harmonic number. The generation
bandwidth, which is, obviously, defined by the duration
of the single spike, reaches the value of \( -\Delta f \approx 200 \text{ GHz} \)
at \(-10 \text{ dB} \). This value can be tuned by the choice of the
parameters of a particular AFM auto-oscillator. In par-
icular, that can be done by tuning the thickness of the
AFM layer, and, therefore, tuning the effective damping
parameter \( \alpha_{eff} \), or by choosing a different AFM mat-
erial having a proper value of the in-plane anisotropy (see
Eq. 2).

As a final remark, we would like to note, that the pro-
posed mechanism of the AFM-based ultra-short spike
generation is efficient for relatively high values of the
damping constant \( \alpha_{eff} \geq 0.01 \). This means that metal-
ic AFM materials, like \( Mn_2Au \) or IrMn could be more
suitable for the practical design of the AFM-based spike
generators, than the dielectric AFM, like NiO. The use
of conductive AFM layers in a spike generator can also
substantially enhance the magnitude of the output signal
by employing the "AFM tunneling magnetoresistance ef-
fet" [23-24] instead of the ISHE in the adjacent Pt layer
to extract the output spike signal from the AFM mate-
rial.

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