

# Ultrafast Sweep-Tuned Spectrum Analyzer with Temporal **Resolution Based on a Spin-Torgue Nano-Oscillator**

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performed on a vortex-state STNO generating in a frequency range around 300 MHz, when frequency down-conversion and matched filtering is used for signal processing. It is shown that this STNO-based spectrum analyzer can perform analysis of frequency-agile signals, having multiple rapidly changing frequency components with temporal resolution in a  $\mu$ s time scale and frequency resolution limited only by the "bandwidth" theorem. Our calculations show that using uniform magnetization state STNOs it would be possible to increase the operating frequency of a spectrum analyzer to tens of GHz.



**KEYWORDS:** Spin-torque nano-oscillators, spectral analysis, signal processing

n modern radar and communication technology, it is important to be able to rapidly analyze the frequency composition of frequency-agile external signals, the frequency content of which is varying on the time scale comparable to the characteristic times of the signal propagation.<sup>1</sup> This problem can be solved by using a spectrum analyzer based on a local voltage-controlled oscillator the generated frequency of which is rapidly sweep-tuned in the interval where the spectrum analysis is performed.<sup>2</sup> The period T of sweep-tuning should be made sufficiently short to be able to continuously monitor the rapid variations of the frequency content of the analyzed signal. Note, at the same time, that the frequency resolution of such a device is limited from below by 1/T, the inverse of the of the signal acquisition time, due to the "bandwidth" theorem.

Recent progress in nanotechnology has led to the development of spin-torque nano-oscillators (STNO), whose time constants due to their nanoscale size are naturally of the order of 1-100 ns.<sup>3</sup> The use of STNOs in sweep-tuned microwave spectrum analyzers could, thus, bring a substantial reduction of the characteristic sweeping times in microwave spectrum analysis and develop spectrum analyzers with fine temporal resolution, which will considerably impact modern radar and communication technologies.

The generation mechanism of STNOs is based on the effect of spin-transfer torque,<sup>4</sup> that creates an effective negative damping in a DC current-driven magnetic tunnel junction structure, and that compensates the natural magnetic damping in the "free" magnetic layer of this structure.<sup>3,4</sup> The frequencies

of the periodic voltage signals generated by STNOs lie in the range from several hundred MHz to several tens of GHz.<sup>3-11</sup> Most importantly, the frequency generated by an STNO strongly depends on the oscillation amplitude, and, therefore, on the amplitude of the bias direct current driving the STNO. This nonisochronous property of STNOs creates the possibility to modulate the generation frequency of an STNO by modulating the magnitude of the driving bias direct current (or voltage).<sup>12–15</sup> Theory<sup>5,6</sup> predicted that the maximum speed, at which the STNO frequency can be modulated by changing the current, is given by the relaxation rate  $\Gamma_p = 2\pi f_p$ . This is the rate with which fluctuations of the amplitude of an STNO-generated signal relax to a quasistationary limit cycle. Experiments have shown that characteristic frequencies  $f_p$  of this relaxation process depend on the STNO configuration and range from  $f_p = 1-10$  MHz for vortex-state STNOs<sup>16</sup> to  $f_p = 100-400$  MHz for uniform magnetized STNOs.<sup>15,17–19</sup> However, it was also predicted<sup>20</sup> and experimentally<sup>21,22</sup> demonstrated that using field modulation it is possible to achieve modulation frequencies on the order of GHz. Hence when using a "sawtooth" modulation

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Figure 1. Schematic of the STNO-based spectrum analyzer consisting of two blocks: block (a) generating a sweep-tuned reference signal  $V_{ref}$  and block (b) performing signal processing resulting in the spectral analysis of the incoming signal  $V_{in}$ . The insets show the voltage signals versus time at different points of the spectrum analyzer circuit: (i) the sweep signal  $V_{sw}$ , (ii) the output of the STNO  $V_{STNO}$ , (iii) the reference signal  $V_{ref}$  produced by the sweep-tuned STNO after filtering and amplification, (iv) the external signal  $V_{in}$ , (v) the mixer output signal  $V_{if}$  (vi) the discretized basis filter function of the matched filter signal, (vii) the output signal  $V_{spec}$  resulting in a peak of duration  $\tau$  and containing the information about the spectrum of the external signal  $V_{in}$ .

signal (either current or field with frequency  $f_{sw}$ ) one can expect to sweep the STNO frequency without significant distortions within sweep times  $T = 1/f_{sw}$  of at least one microsecond for vortex based STNO, but that could, potentially, be as fast as 1–10 ns for other STNO configurations.

In a recent theoretical paper,<sup>23</sup> it was proposed to use such a sweep-tuned STNO as a central element of a novel ultrafast spectrum analyzer where signal mixing and correlation processing using low-pass and matched filters were involved.

Here we demonstrate a proof-of-principle experimental realization of this method of fast spectrum analysis<sup>23</sup> for the case of vortex-based magnetic tunnel junction STNOs generating stable sinusoidal signals in the 280–320 MHz frequency range and characterized by an amplitude relaxation frequency of  $f_p = 2-3$  MHz. The largest frequency sweeping rates  $\rho_{sw}$  in our experiments were exceeding  $\rho_{sw} = \Delta F_{sw}/T = 30$  MHz/ $\mu$ s for a frequency span of  $\Delta F_{sw} = 20$  MHz, allowing us to achieve spectrum analysis of complex multitone and frequency manipulated signals with temporal resolution on the  $\mu$ s time scale.

**Results.** The scheme of the experimental STNO-based device used to perform spectrum analysis in our experiments is shown in Figure 1. It consists of two blocks: the block (a) containing an STNO and used for generation of a sweep-tuned reference signal  $V_{\text{ref}}$  and the block (b) used for signal processing and eventual spectrum analysis of an external signal  $V_{\text{in}}$ .

 $V_{\rm in}$ . The sweep-tuned reference signal  $V_{\rm ref}$  is produced as follows. First, a constant DC current  $I_{\rm DC}$  is applied to the STNO to generate a sinusoidal auto-oscillation signal of a constant carrier frequency  $f_0$ . Then an additional voltage  $V_{\rm sw}$  having a "sawtooth" shape in time and a frequency  $f_{\rm sw} = 1/T$  is applied to the STNO via a coupler. The amplitude of  $V_{\rm sw}$  is adjusted in such a way that the frequency of the auto-oscillation signal generated by the STNO sweeps between two values  $f_1$  and  $f_2$ , around  $f_0$  with a span  $\Delta F_{sw} = f_2 - f_1$ . After passing through a band-pass filter and an amplifier, the reference signal,  $V_{ref}$  has a frequency chirp with the instantaneous frequency  $f_{ref}(t)$  that changes in time.

For the analysis of an external signal  $V_{\rm in}$  of an unknown frequency  $f_{\rm in}$ , the reference signal  $V_{\rm ref}$  along with the external signal  $V_{\rm in}$ , is supplied to the mixer situated in the block (b). For signal mixing, we used a commercially available mixer (AD831) having an output cutoff frequency of  $F_{\rm F} = 200$  MHz, and, therefore performing the function of a low-pass filter with a bandwidth of  $\Delta F_{\rm F} = 200$  MHz. We note that in our experiments the sweeping frequency interval  $\Delta F_{\rm sw} = 20$  MHz was much smaller than the mixer bandwidth of  $\Delta F_{\rm F}$ , so that the frequency resolution of the spectrum analysis was determined only by the sweeping frequency  $f_{\rm sw}$ .

The output signal of the mixer  $V_{if}$  has the intermediate frequency  $f_{if}(t)$  equal to the difference of frequencies of the mixed signals  $f_{if}(t) = f_{ref}(t) - f_{in}$ . This instantaneous frequency goes to zero at a certain time  $t_0$ , when  $f_{ref}(t_0) = f_{in}$ . Note that the component of the mixed signal having the frequency  $f_{ref}(t)$ +  $f_{in}$  was removed due to the  $F_F$  output cutoff frequency of the mixer.

The output signal  $V_{\rm if}$  of the mixer is then digitized using an 8-bit AD9280 analog-to-digital converter (ADC), and passed through a matched filter, implemented with a field programmable gate array (FPGA), to compress this signal into a narrow peak of duration  $\tau$  in  $V_{\rm spec}$ . The matched filter output is then converted back into the analog domain using an 8-bit resolution AD9708 digital-to-analog converter (DAC) and is visualized on a single shot oscilloscope.

The temporal position of the maximum of the peak in  $V_{\text{spec}}$  determines the frequency of the input signal  $f_{\text{in}}$ , while the temporal width of this peak  $\tau$  characterizes the resolution bandwidth (RBW), or accuracy of the frequency analysis:

$$\Delta F_{\rm RBW} = \rho \tau = \Delta F_{\rm sw} \frac{\tau}{T} \tag{1}$$

We used in our signal processing protocol a matched filter instead of a conventional band-pass filter with envelope detection to achieve a resultant peak having a single maximum and a minimum possible duration  $\tau$ , which is independent of the phase difference between the input signal  $V_{\rm in}$  and the STNO-generated reference signal  $V_{\rm ref}$  (see ref 23 for details). Details on the matched filter configuration and implementation can be found in the Methods and Supporting Information.

To demonstrate experimentally the STNO-based spectrum analysis, we have chosen a relatively low frequency (~300 MHz) vortex-state STNO as STNOs of this type have rather large output power of order of  $\mu$ W and typical line width of a few hundred kHz.<sup>16,24,25</sup> The results are presented for two different devices, although many other devices demonstrated very similar results (see Methods section for details on the devices and their fabrication).

Figure 2 shows a free-running frequency-voltage characteristic  $f_0(V)$  of a representative vortex-state STNO device



**Figure 2.** Nonlinear frequency-voltage characteristics  $f_0(V)$  of the vortex-state STNO used in our experiments, performed under an out-of-plane bias magnetic field of  $H_{\perp} = 3$  kOe.

obtained under the action of an applied out-of-plane bias magnetic field  $H_{\perp} = 3$  kOe. It is clear from Figure 2 that when the DC voltage applied to the STNO is varied between 0.23 and 0.37 V, the frequency generated by the STNO is a nonlinear (convex) function of voltage, and varies between  $f_1 = 287$  MHz and  $f_2 = 307$  MHz ( $\Delta F_{sw} = 20$  MHz) with a typical line width (full width at half-maximum (fwhm)) of its power spectrum equal to  $\Delta \omega / 2\pi = 0.25$  MHz. This nonlinearity can be compensated by using a nonlinear (concave) profile of a "quasi-sawtooth" voltage applied to the STNO, which makes it possible to obtain a purely linear time dependence of the chirped frequency in the signal  $V_{ref}$  generated by the sweeptuned STNO (see Supporting Information for details).

First, we present the results of the analysis of a monochromatic sinusoidal signal  $V_{in}$  to demonstrate that (i) using a vortex STNO-based spectrum analyzer, one can achieve frequency sweep rates of the order of MHz/ $\mu$ s and sweeping frequencies of the order of MHz, and (ii) the resolution in external frequency determination is close to the theoretical limit for fast spectrum analysis. Then, we demonstrate that the STNO-based spectrum analyzer is

capable of performing the analysis of signals having a complex frequency spectrum with time-varying frequency components.

The experimental results are shown in Figure 3 demonstrating the analysis of a monochromatic (single-tone) sinusoidal signal ( $f_{\rm in} = 300$  MHz,  $P_{\rm in} = 1.0$  mW) supplied to the spectrum analyzer from a commercial signal generator. The three panels in Figure 3 show: (top) the sweeping "sawtooth" voltage  $V_{\rm sw}$  having the frequency  $f_{\rm sw} = 1/T = 0.4$  MHz; (middle) the chirped-frequency signal  $V_{\rm if}$  obtained after the mixer; (bottom) the output signal from the matched filter  $V_{\rm spec}$  measured using a standard oscilloscope.

At the time  $t_0 \approx 1.25 \ \mu s$  (corresponding to  $V_{sw} = 0$ ) the STNO frequency  $f_{ref}(t_0)$  is the same as the frequency of the external signal  $f_{in}$  = 300 MHz, resulting in a frequency difference  $f_{if}(t_0) = f_{ref}(t_0) - f_{in} = 0$ . It is this moment, which must be identified and measured. The chirped signal  $V_{if}$  after passing through a matched filter is squeezed in time, and forms in the output signal  $V_{\rm spec}$  a pronounced peak of the duration auat  $t = t_0 + \tau_{\text{ME}'}$  where the  $\tau_{\text{ME}}$  is the time delay in the matched filter. The stability of the delay time  $au_{\mathrm{MF}}$  is determined by the phase noise of an FPGA fixed-frequency clock generator, which is, generally, much more stable than any VCOs.<sup>26</sup> Therefore, the influence of the instability of  $au_{\mathrm{MF}}$  on the accuracy of the frequency determination at the used sweep rates  $f_{sw}$  can be neglected, and the magnitude of  $au_{\mathrm{MF}}$  can be considered constant. Taking into account the constant time delay  $\tau_{\rm MF}$  in the matched filter, one can, thus, correctly identify the frequency of the input signal by the temporal position of the output peak (see bottom panel and the corresponding frequency scale to the right in the top panel).

The accuracy of the frequency determination using the STNO-based spectrum analyzer, characterized by the frequency resolution bandwidth  $\Delta F_{\text{RBW}}$ , can be evaluated from the experimentally measured magnitude of the peak duration  $\tau$  using eq 1 (see Figure 4).

In Figure 4a, we present the results of the spectrum analysis  $(V_{\text{spec}}(t))$  of a monochromatic external signal for three different sweeping frequencies  $f_{\text{sw}} = 0.1$ , 0.8, and 1.5 MHz, while in Figure 4b we compare the experimentally obtained frequency resolution bandwidth  $\Delta F_{\text{RBW}}$  with a theoretical limit obtained from the "bandwidth" theorem  $\Delta F_{\text{RBW}} = f_{\text{sw}} = 1/T$ .

It is clear that for the smaller sweeping frequencies the frequency resolution bandwidth  $\Delta F_{\rm RBW}$  of the spectrum analysis will be limited from below by the STNO generation line width  $\Delta \omega / 2\pi = 0.25$  MHz.<sup>27–30</sup> However, as it can be seen from Figure 4, for sufficiently large sweeping frequencies,  $f_{\rm sw} > 0.1$  MHz ( $\rho_{\rm sw} > 2$  MHz / $\mu$ s), the experimentally obtained frequency resolution bandwidth  $\Delta F_{\rm RBW}$  is very close to the theoretical limit defined by the "bandwidth" theorem, which means that a large generation line width of an STNO and its relatively high phase noise have practically no influence on the resolution bandwidth  $\Delta F_{\rm RBW}$  in the proposed method of ultrafast spectrum analysis.

The results presented so far demonstrate the basic properties of the STNO-based spectrum analyzers when working with simple monochromatic external signals. Below, we demonstrate that STNO-based spectrum analyzers can work successfully with rather complex external signals having many different frequency components that can vary in time.

The first example is given in Figure 5a where we demonstrate spectrum analysis of an external signal that is a superposition of two single-tone continuous signals supplied from two commercial signal generators with frequencies  $f_{in1}$  =



**Figure 3.** (two column figure): Spectral analysis of a single-tone external sinusoidal signal ( $f_{in} = 300 \text{ MHz}$ ,  $P_{in} = 1.0 \text{ mW}$ ): sweeping voltage signal  $V_{sw}$  (top panel),  $V_{if}$  (middle panel), and  $V_{spec}$  (bottom panel) for  $f_{sw} = 0.4 \text{ MHz}$  taken at different points of the spectrum analyzer setup (see insets (i), (v), and (vii) of Figure 1). The experimental frequency resolution  $\Delta F_{RBW}$  was calculated using (1) from the experimentally measured peak duration  $\tau$  (see bottom panel).



**Figure 4.** (a) Results of the spectrum analysis ( $V_{spec}(t)$ ) of a monochromatic external signal for three different sweeping frequencies  $f_{sw} = 0.1, 0.8$ , and 1.5 MHz. (b) Resolution bandwidth (RBW) of the spectrum analysis  $\Delta F_{RBW}$  as a function of the sweeping frequency  $f_{sw}$ . The values of corresponding to the light blue dots presented in panel b were calculated from the measured values of the resulting peak duration  $\tau$  using eq 1. Error analysis was done on four random consequent measurements of the peak duration  $\tau$ . The straight dark blue line in Figure 4(b) was calculated from the "bandwidth" theorem:  $\Delta F_{RBW} = f_{sw} = 1/T$ . The dashed vertical line shows the value of the experimental vortex STNO relaxation frequency  $f_p$  for amplitude fluctuations limiting the upper modulation frequency of the STNO-generated signal (see refs 5, 15, and 16 for details).

300 MHz, and  $f_{in2} = 306$  MHz. The top panel in Figure 5a shows the linear voltage sweep  $V_{sw}$  at  $f_{sw} = 0.3$  MHz, while the vertical dashed lines show the positions where the sweeping STNO frequency equals the frequency components contained in the external signal. The bottom panel of Figure 5a shows the resultant voltage  $V_{spec}$  at the output of the matched filter with two distinct peaks, which occur at times corresponding to the frequency components  $f_{in1}$  and  $f_{in2}$  in the input signal. Note

that the time shift between the linear sweep voltage  $V_{\rm sw}$  and the resultant voltage  $V_{\rm spec}$  at the output of the matched filter (see Figure 3) caused by the time delay  $\tau_{\rm MF}$  in the matched filter was not shown in Figure 5a-c.

Figure 5b shows the result of the frequency analysis of an external signal whose frequency is hopping between the values of  $f_{in1}$  = 301 MHz and  $f_{in2}$  = 299 MHz. This experiment demonstrates that the STNO-based spectrum analyzer can

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**Figure 5.** Spectrum analysis of complex external input signals  $V_{in}$ . (a) Two-tone signal containing frequency components  $f_{in1} = 300$  MHz and  $f_{in2} = 306$  MHz. (b) Signal with a frequency that is hopping between two close values of  $f_{in1} = 301$  MHz and  $f_{in2} = 299$  MHz; (c) Signal with a frequency that is varying continuously in a sinusoidal fashion with the period  $T_{10} = 10$   $TT_{10} = 10T = 20$ ? s, where *T* is the sweeping period. Top panel shows the nonlinear sweeping voltage  $V_{sw}$ , middle panel shows the resultant peaks  $V_{spec}$  with temporal positions varying within each sweeping period, while the bottom panel shows the experimentally obtained variation of the external signal frequency. (d) Signals with various modulation patterns with the period  $T_{10} = 10T = 20 \ \mu s$  and arbitrary initial phases of modulation. Top panel shows the signal with the shift-keyed frequency between 295 and 305 MHz. Middle and bottom panels show the signals whose frequency is varying discontinuously in a "sawtooth" fashion with increasing and decreasing frequency, respectively. The frames at the right show the results of a conventional spectrum analysis for the same signals.

easily detect the changes of external frequency in time if these changes are happening on the time scale that is larger than the period T of the STNO frequency sweep. This property will be very important to efficiently analyze signals of modern radar where frequency hopping protocols are used.

The ultimate demonstration of the potential of the STNObased sweep-tuned spectrum analyzer is given in Figure 5c and d where the analysis of complex external signals whose frequency is continuously or discontinuously changing in time is illustrated. If such changes are happening on the time scale  $T_n = nT$  that is  $n \ge 2$  times larger, than the STNO sweeping period *T*, the STNO-based spectrum analyzer successfully tracks the temporal evolution of the frequency of the external signal. In particular, in Figure 5c, the frequency of the external signal varies in time between  $f_{\min} = 295$  MHz and  $f_{\max} = 305$ MHz in a sinusoidal fashion with the period  $T_{10} = 10T$  ( $f_{sw} = 1/T = 0.5$  MHz).

In such a case, to recover the true temporal frequency variation in the external signal, we performed the compensation of nonlinearity of the STNO characteristics  $f_0(V)$  Figure 2 (see Supporting Information for details) and used a nonlinear (concave) sweeping voltage signal  $V_{sw}$  (see the top panel in

Figure 5c). The peaks in the signal  $V_{\text{spec}}$  having different temporal positions corresponding to different instantaneous frequencies of the external signal measured during consequent sweeping periods are shown in the middle panel of Figure 5c, while the resultant temporal evolution of the frequency of the external signal  $f_{\text{in}}(t)$  is shown in the bottom panel of Figure 5c. In this panel, the frequency axis is simply the corresponding frequency scale of a single sweeping period of the middle frame of the same figure.

Finally in the three panels of Figure 5d we show a similar result of the analysis of input signals where the frequency experiences discontinuous shift keying (top panel) and sawtooth-like temporal variations with either increasing (middle panel) or decreasing (bottom panel) frequency. It is clear that, in a sweep-tuned spectrum analysis based on an STNO, it is possible to reveal and analyze any fast-changing modulation patterns, while the power spectra obtained with a conventional frequency-swept spectrum analyzer (shown in panels to the right in Figure 5d) for sawtooth signals with increasing and decreasing frequencies are very similar, and demonstrate only the same interval of frequency variation in

**Conclusion.** In this work, a novel approach to timeresolved high-speed spectrum analysis was experimentally demonstrated. The key element used in this method is a nanosized active STNO device that plays the role of a sweeptuned oscillator. The nanoscale size brings the advantage of short intrinsic time constants that, together with the excellent tunability of STNOs, makes possible a rapid sweep-tuning of the STNO frequency. The repetition of the fast tuning of the STNO through the studied frequency range brings the capability of temporal resolution in the spectral analysis of the frequency-agile signals.

The proof-of-principle experimental demonstration for this STNO-based spectrum analysis was performed using a vortexstate STNO characterized by generation frequencies around 300 MHz with a maximum modulation or sweep frequency of  $f_{sw}^{max} = 1.5$  MHz, and the shortest time interval of spectrum analysis  $T_{minmin} = 0.67 \ \mu s.$ 

We demonstrated fast time-resolved spectrum analysis of complex dynamically modulated signals (see Figure 5), that is not possible to achieve using conventional swept-tuned spectrum analyzers, with the frequency resolution  $\Delta F_{\rm RBW}$  that, at sufficiently high sweeping rates, is independent of the STNO generation line width  $\Delta \omega / 2\pi$ , and is limited only by the "bandwidth" theorem (see Figure 4b).

Finally, it is important to discuss the possibilities of the further development of the time-resolved method of microwave spectrum analysis proposed in this work. Several points need to be considered for this: (i) the STNO generation frequency should be substantially increased to detect signals in the 1-10 GHz range and possibly beyond, (ii) the tunable frequency range (bandwidth) should be made as large as possible, while the dependence of the generated frequency of bias current (or voltage) should be continuous and free of jumps, (iii) the sweep frequency of the spectrum analyzer should be increased to be able to detect the frequency variation in the analyzed signals in the nanosecond range, and (iv) the free-running generation line width should be lower than the sweep rate  $\Delta \omega / 2\pi < 1/T$  for the RBW to be limited by the "bandwidth" theorem, and not by the STNO generation line width.

It has been demonstrated experimentally<sup>31-35</sup> and by our theoretical estimations<sup>5,23</sup> that these conditions can be simultaneously fulfilled using STNO devices having a uniformly magnetized "free" layer. First of all, they can generate frequencies of up to several tens of GHz.<sup>3,7-11</sup> Several examples exist for nanopillar devices (see refs 32-35) but also for uniform-magnetic-state nanocontact STNOs biased by sufficiently large (exceeding 1.0 T) bias magnetic fields (see for example, ref 31). However, for practical devices the creation of such large bias magnetic fields could be technically challenging, and the use of uniform-magnetic-state nanopillar STNOs with, for example, perpendicular anisotropy capable of working in the GHz frequency range with near-zero bias magnetic fields<sup>32-35</sup> seems to be a more practical option. Second, for uniformly magnetized STNO devices it has been demonstrated that the frequency can be tuned via the current (or voltage) over relatively large frequency ranges (several GHz<sup>34</sup>). To further increase the frequency range, one may think about using an array of devices where each next device covers a frequency range that is adjacent to the range of a previous one. For stacks with perpendicular magnetic anisotropy (polarizer

or free layer) this is possible by varying the nanopillar size and shape. Third, it has been demonstrated that the uniformly magnetized devices can be modulated with frequencies reaching several hundred MHz,<sup>15,19</sup> where the modulation frequency is limited by the STNO intrinsic relaxation rate  $\Gamma_p$  of the amplitude fluctuations.<sup>5</sup> The high values of  $\Gamma_p$  are needed to achieve high rates of frequency sweeping (modulation). Experiments<sup>20–22</sup> have demonstrated that relaxation rates  $\Gamma_p$  in the GHz frequency range can be achieved, which corresponds to the possible frequency sweeping periods in the ns range. In addition,  $\Gamma_p$  can be increased when using high values of the bias DC current (see section V in ref 5 for details).

To conclude, the STNO-based ultrafast time-resolved spectrum analysis at high microwave frequencies with high frequency resolution is a solvable engineering problem, requiring mainly an appropriate adjustment of known STNO device configurations. We firmly believe that the ultrafast STNO-based spectrum analyzers with nanosecond temporal resolution will become in the near future practical and highly competitive microwave signal processing devices.

Methods. MTJ Devices. The STNOs used for the experiments are magnetic tunnel junction nanopillar devices with a vortex-state configuration of the free layer. The devices, realized at the International Iberian Nanotechnology Laboratory (INL), have the following composition (thicknesses in nm): substrate/6 IrMn/2.6 CoFe30/0.85 Ru/1.8 CoFe40B20/ MgO/2.0 CoFe40B20/0.2 Ta/7 NiFe/10 Ta. The materials were sputter deposited using a Singulus Rotaris machine and were nanofabricated using ion beam and chemical etching techniques. Best signal generation properties in terms of phase noise and frequency tuning were obtained for nanopillar diameters of 300-400 nm. The corresponding frequencies lie in the range of 270-330 MHz when applying an out-of-plane field  $H_{\perp}$  at a small in-plane tilt angle of  $1-5^{\circ}$ . For the results presented in the manuscript, we used a permanent magnet at variable distance to produce an out-of-plane field of  $H_{\perp} \approx 3$ kOe. Results are presented for devices that had a diameter of 370 nm, a parallel resistance of  $R_{\text{STO}} \approx 40\Omega$ , a TMR  $\approx 150\%$ , and an RA  $\approx 3 \Omega \mu m^2$ .

Experimental Setup. Free Running STNO. The characterization of the free running signal was done with the setup of Figure 1, where  $V_{sw}$  was set to zero and the STNO signal  $V_{\rm STNO}$  after an amplification of 20 dB was analyzed using a spectrum analyzer or a single shot oscilloscope. From the spectrum analyzer measurements, we obtain the frequency  $f_{0}$ , full width half-maximum line width and output power of the STNO signal after subtraction of the measurement gain. Representative results are shown in the Supporting Information Figure S1. From the time traces registered on the oscilloscope, we extract the instantaneous frequency and phase of the STNO using the method of the Hilbert transform.<sup>16–18</sup> This method was used to determine the amplitude relaxation frequency,<sup>16,18</sup> the instantaneous STNO frequency when applying the sweep voltage  $V_{sw}$  and to verify the compensation of the frequency-voltage nonlinearity (Figure S2 in Supporting Information Section II).

*SA.* The spectrum analyzer setup described in Figure 1 differs slightly from the one proposed in ref 23 where the mixing of the reference signal  $f_{ref}(t)$  and the input signal  $f_{in}$  was proposed to occur within the STNO, without an external mixer. Since the frequency range of the mixed signal  $V_{if}$  is close to the frequency range of  $V_{sw}$  and therefore the ranges may overlap, it is not always possible to well separate these signals

using filters. Therefore,  $V_{sw}$  was removed from  $V_{STNO}$  before mixing using a band-pass filter with a range of 250–350 MHz and the mixing was achieved using an external mixer.

*Matched Filter.* The matched filter employed for the experiment, uses a finite impulse response (FIR) architecture and was implemented with FPGA (Xilinx XC6SLX9) with a discretized basis filter function (see Supporting Information for details). The same matched filter coefficient values were used for all results shown in Figures 3-5. To adopt the matched filter for different sweep rates, its clock frequency was proportionally changed so that the basis function and the measured  $V_{\rm if}$  signals had the same scale.

### ASSOCIATED CONTENT

#### **Supporting Information**

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.nanolett.0c02195.

Basic characterization of STNO used in experiments, details on compensation of STNO frequency-voltage nonlinearity and implementation of matched filter (PDF)

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#### **Author Contributions**

A.L. and U.E. conceived the experiments; A.L. designed the matched filter and the experiment; A.L., V.I., and P.S. performed the measurements and analyzed the data; S.L., J.L., V.T., and A.S. performed theoretical calculations; A.J. and R.F. prepared the samples; A.L., U.E., and A.S. wrote the manuscript with help from S.L.; A.S. and U.E. managed the project; all authors contributed to the manuscript, the discussion, and analysis of the results.

#### Notes

The authors declare no competing financial interest.

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### ABBREVIATIONS

STNO, spin-torque nano-oscillator; RBW, resolution bandwidth; ADC, analog-to-digital converter; FPGA, field programmable gate array; DAC, digital-to-analog converter; FIR, finite impulse response

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