

Classification tasks using input driven nonlinear magnetization dynamics in spin Hall oscillator

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Supporting Materials

Supplementary material 1

Ferromagnetic resonance.

Supplementary material 2

Investigation of magnetization dynamics and 4-bit digit pattern separation on regular pulse scheme with $I_0 = 0$, $I_1 = 4.0$ & 6.0 mA, $\Delta t = 4$ ns, $\tau = 3$ ns.

Supplementary material 3

Investigation of magnetization dynamics and 4-bit digit pattern separation on regular pulse scheme with $I_0 = 0$ mA, $I_1 = 3.5$ mA, $\Delta t = 4$ ns, $\tau = 1.5$ ns & 3.6 ns.

Supplementary material 4

Magnetization dynamics of 16 combinations of 4-bit digit pattern separation on modified pulse scheme with $I_e = 3.0$ mA, $\delta = 5$ ns, $I_0 = 1.2$ mA, $I_1 = 2.4$ mA, $\Delta t = 4$ ns, $\tau = 3.0$ ns.

Supplementary material 5

Investigation of magnetization dynamics and 4-bit digit pattern separation on modified pulse scheme with $I_e = 1.4$ mA, $\delta = 5$ ns, $I_0 = 1.2$ mA, $I_1 = 2.4$ mA, $\Delta t = 4$ ns, $\tau = 3$ ns.

Supplementary material 6

Investigation of magnetization dynamics and 4-bit digit pattern separation on modified pulse scheme with $I_e = 5.0$ mA, $\delta = 5$ ns, $I_0 = 1.2$ mA, $I_1 = 2.4$ mA, $\Delta t = 4$ ns, $\tau = 3$ ns.

Supplementary material 7

Investigation of magnetization dynamics and 4-bit digit pattern separation on modified pulse scheme with $I_e = 5.0$ mA, $\delta = 1, 20$ & 25 ns, $I_0 = 1.2$ mA, $I_1 = 2.4$ mA, $\Delta t = 4$ ns, $\tau = 3$ ns.

Supplementary material 1: Ferromagnetic resonance.

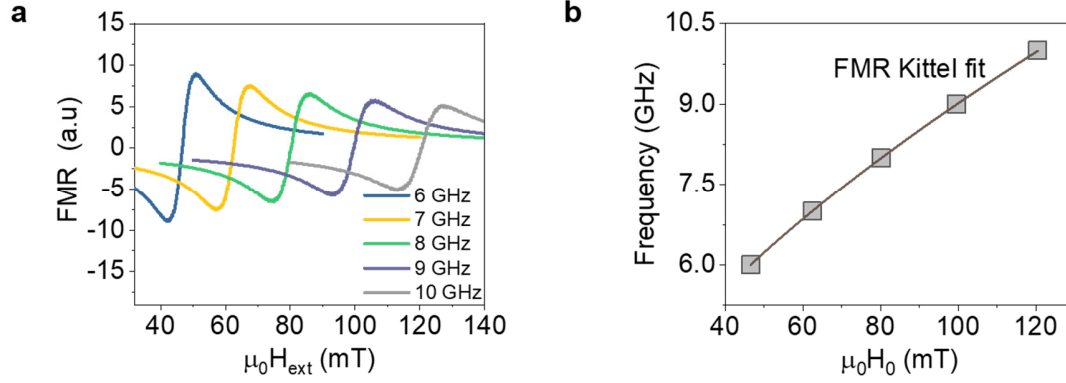


Figure S1. a. Simulated ferromagnetic resonance (FMR) for modelled spin Hall oscillator (SHO) in the main text. The applied magnetic field (H_{ext}) is oriented along Y axis and the oscillating magnetic field (H_{rf}) at a fixed microwave frequency is applied along X axis with a strength of 1 mT. The H_{ext} is swept for fixed frequency. **b.** The obtained resonant field (H_0) as a function of the applied frequency. The data are fitted with the Kittel equation $f = \mu_0 \gamma / 2\pi \sqrt{H_0(H_0 + M_{\text{eff}})}$ yielding an effective magnetization, $\mu_0 M_{\text{eff}} = 1.0$ T with gyromagnetic ratio $\gamma/2\pi = 27.3$ GHz/T.

Supplementary material 2: Investigation of magnetization dynamics and 4-bit digit pattern separation on regular pulse scheme with $I_0 = 0$, $I_1 = 4.0$ & 6.0 mA, $\Delta t = 4$ ns, $\tau = 3$ ns.

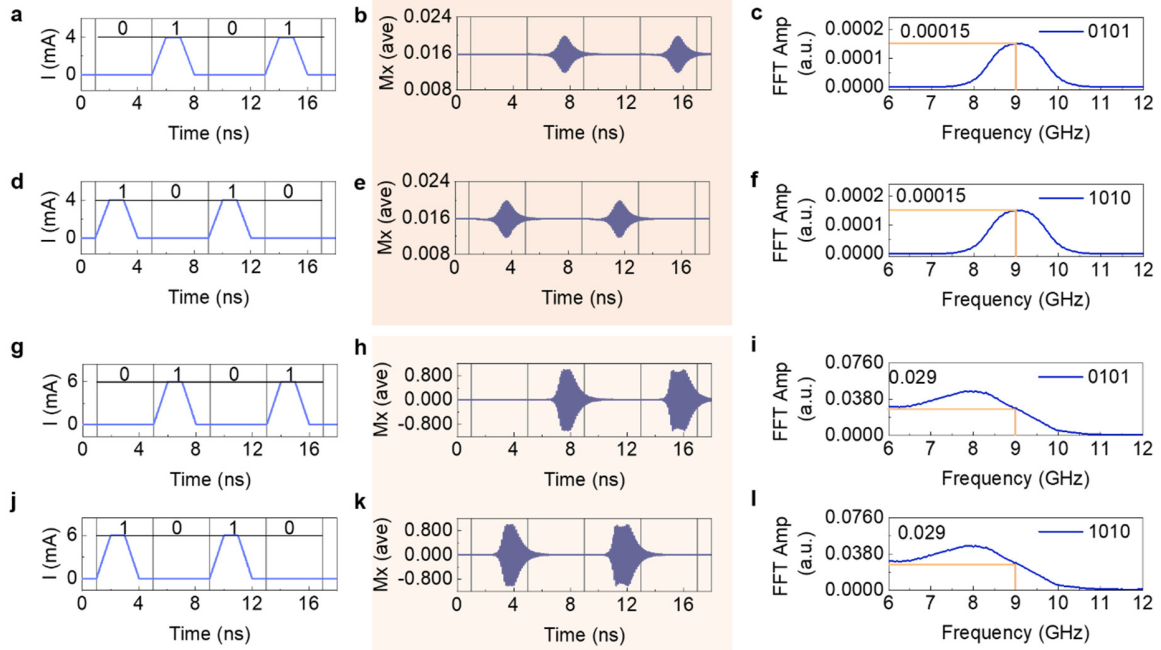


Figure S2. Figures **a** and **d** show the 4-bit binary input pulse patterns with input parameters $I_0 = 0$, $I_1 = 4.0$ mA, $\Delta t = 4$ ns and $\tau = 3$ ns, for the 4-bit patterns 0101 and 1010 respectively. For both pattern 0101 and pattern 1010, the M_x oscillation amplitudes in the Figs. **b** and **e** corresponding to the input bit 1 are the same. This prevents the separation of the two patterns as can be seen from the similar value of FFT amplitude in Figs **c** and **f**. Figures **g** and **j** show the 4-bit binary input pulse with input parameters with I_1 in the nonlinear regime $I_0 = 0$, $I_1 = 6.0$ mA, $\Delta t = 4$ ns and $\tau = 3$ ns, for the 4-bit patterns 0101 and 1010 respectively. For both pattern 0101 and pattern 1010, the M_x response is auto-oscillations as shown in the Figures **h** and **k**, where bit 1 pulses oscillate at the same amplitude level. This again prevents the separation of the two patterns as seen from the similar value of FFT amplitude at the filtering frequency of 9.0 GHz as shown the Figs **i** and **l**.

Supplementary material 3: Investigation of magnetization dynamics and 4-bit digit pattern separation on modified pulse scheme with $I_0 = 0$ mA, $I_1 = 3.5$ mA, $\Delta t = 4$ ns, $\tau = 1.5$ ns & 3.6 ns.

ns.

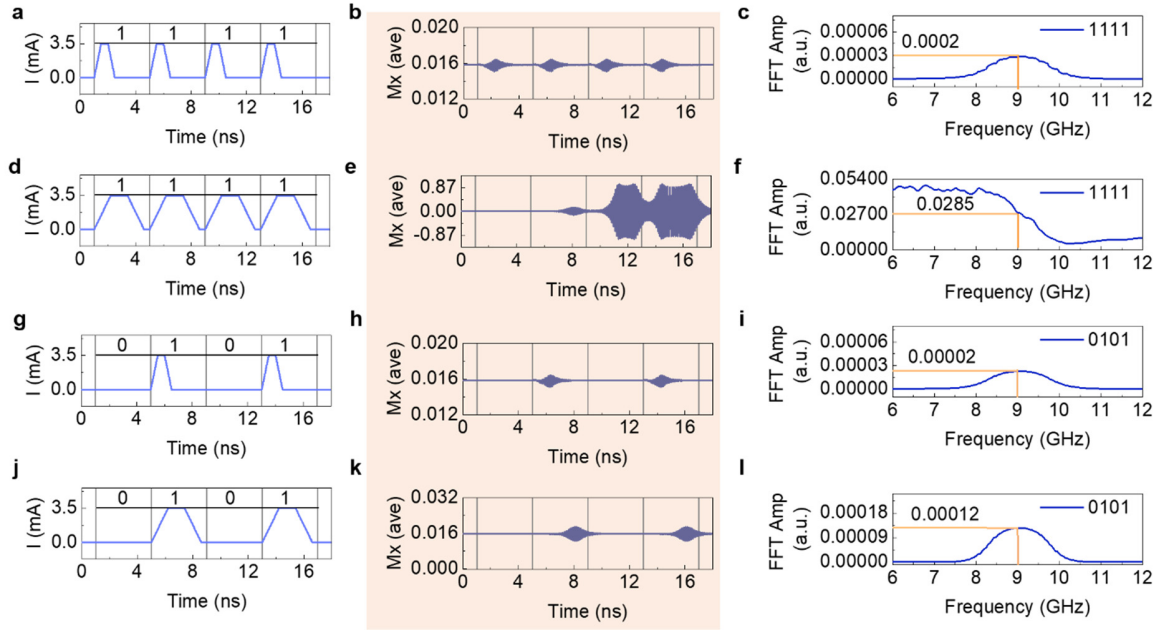


Figure S3. Figure. **a(d)** shows the 4-bit binary input pulse with input parameters $I_0 = 0$, $I_1 = 3.5$ mA, $\Delta t = 4$ ns and $\tau = 1.5$ ns (3.6ns), for the 4-bit pattern 1111. For $\tau = 1.5$ ns (Fig. **b**), due to the relaxation of the excited small angle precession, M_x amplitudes corresponding to each of input bit 1 pulses are the same. However, for $\tau = 3.6$ ns (Fig. **e**), the next bit 1 pulse arrives before the relaxation of the previously excited M_x precession, leading to progressively increasing amplitudes of oscillation. Figures **c** and **f** give the FFT amplitude spectra for 4-bit pattern 1111 for $\tau = 1.5$ ns & 3.6 ns respectively. Figure **g (j)** shows the 4-bit binary input pulse with input parameters $I_0 = 0$, $I_1 = 3.5$ mA, $\Delta t = 4$ ns and $\tau = 1.5$ ns (3.6ns), for the 4-bit pattern 0101. For both $\tau = 1.5$ ns (Fig. **h**) and $\tau = 3.6$ ns (Fig. **k**), the M_x amplitudes corresponding to both the bit 1 pulses are the same. Figures **i** and **l** give the FFT amplitude spectra for 4-bit pattern 1111 for $\tau = 1.5$ ns & 3.6 ns respectively. Similar to Supporting information section S3, this prevents the separation of any cyclic permutations of 4-bit patterns for both $\tau = 1.5$ ns and $\tau = 3.6$ ns.

Supplementary material 4: Magnetization dynamics of 16 combinations of 4-bit digit pattern separation on modified pulse scheme with $I_e = 3.0$ mA, $\delta = 5$ ns, $I_0 = 1.2$ mA, $I_1 = 2.4$ mA, $\Delta t = 4$ ns, $\tau = 3.0$ ns.

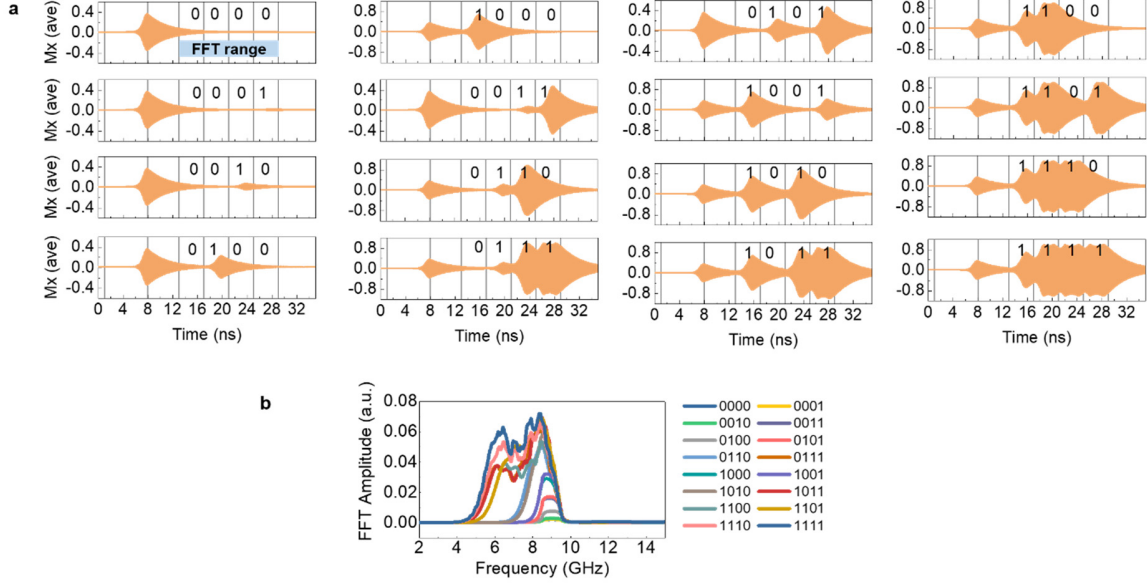


Figure. S4. Figure **a** shows the magnetization dynamics corresponding to the 16 different 4-bit input patterns for the modified pulse scheme with input parameters $I_e = 3.0$ mA, $\delta = 5$ ns, $I_0 = 1.2$ mA, $I_1 = 2.4$ mA, $\Delta t = 4$ ns, $\tau = 3.0$ ns. Figure **b** gives the FFT amplitude spectra corresponding to the 16 different 4-bit input patterns. Note that the FFTs are calculated using M_x in the range of the input patterns as shown in the 0000 bit pattern.

Supplementary material 5: Investigation of magnetization dynamics and 4-bit digit pattern separation on modified pulse scheme with $I_e=1.4$ mA, $\delta=5$ ns, $I_0=1.2$ mA, $I_1=2.4$ mA, $\Delta t=4$ ns, $\tau=3$ ns.

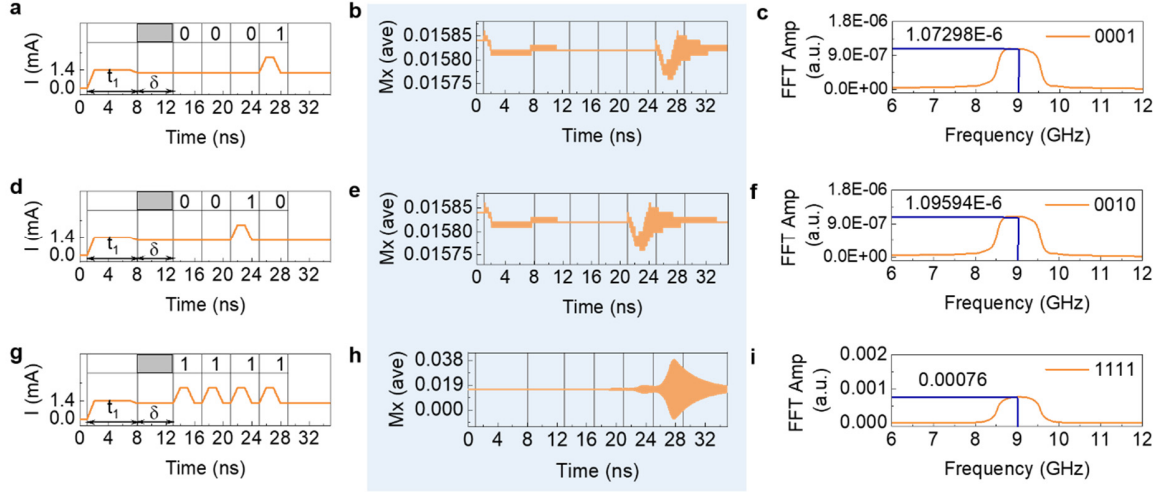


Figure S5. Figures **a**, **b** and **c** show the 4-bit binary input pulse, corresponding magnetization dynamics and FFT amplitude spectra respectively for the 4-bit pattern 0001 with input parameters $I_e=1.4$ mA, $\delta=5$ ns, $I_0=1.2$ mA, $I_1=2.4$ mA, $\Delta t=4$ ns, $\tau=3$ ns. Similarly, Figs. **d** (**g**), **e** (**h**) and **f** (**i**) show the 4-bit binary input, pulse corresponding magnetization dynamics and FFT amplitude spectra respectively for the 4-bit pattern 0010 (1111) with the same input parameters. Note the difference between the FFT amplitude values filtered at 9.0 GHz. The low value of separability index (SI) reported for $I_e=1.4$ mA can be directly correlated with filtered FFT amplitude values in close range for the different 4-bit input patterns.

Supplementary material 6: Investigation of magnetization dynamics and 4-bit digit pattern separation on modified pulse scheme with $I_e=5.0$ mA, $\delta=5$ ns, $I_0=1.2$ mA, $I_1=2.4$ mA, $\Delta t=4$ ns, $\tau=3$ ns.

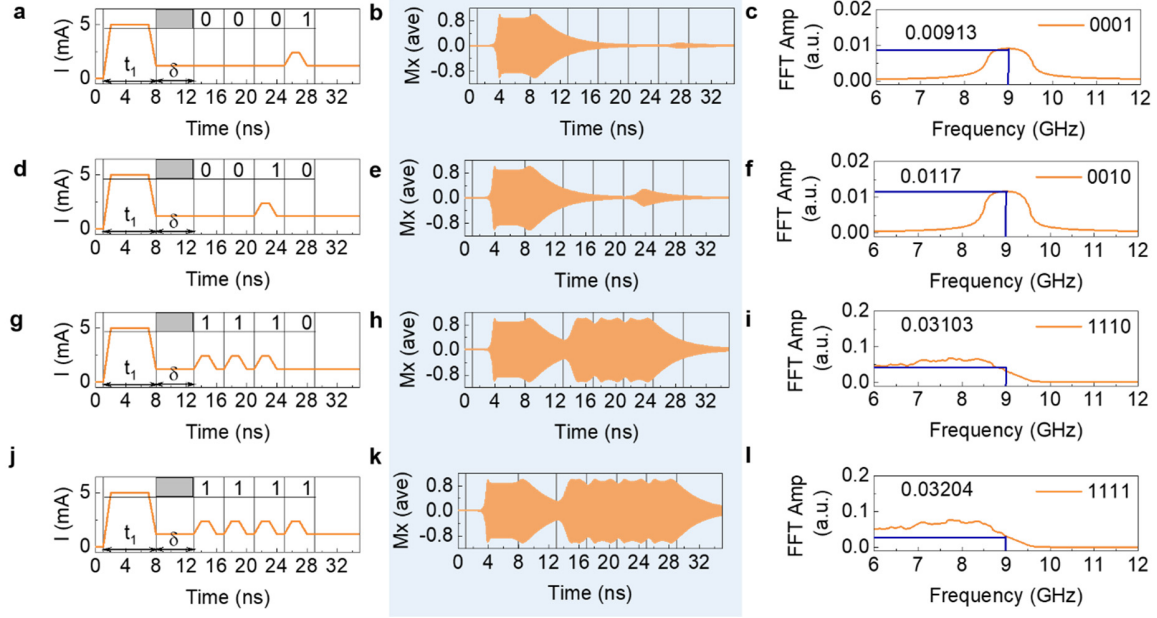


Figure. S6. Figures a(d), b(e) and c(f) show the 4-bit binary input pulse, corresponding magnetization dynamics and FFT amplitude spectra respectively for the 4-bit pattern 0001 (0010) with input parameters $I_e=5.0$ mA, $\delta=5$ ns, $I_0=1.2$ mA, $I_1=2.4$ mA, $\Delta t=4$ ns, $\tau=3$ ns. Similarly, Figures g(j), h(k) and i(l) show the 4-bit binary input pulse, corresponding magnetization dynamics and FFT amplitude spectra respectively for the 4-bit pattern 1110(1111) with the same input parameters. Note the difference between the FFT amplitude values filtered at 9.0 GHz. The high value of separability index(SI) reported for $I_e=5.0$ mA can be directly correlated with the filtered FFT amplitude values for the different 4-bit input patterns. However, the SI for $I_e=5.0$ mA is lower than that of $I_e=3.0$ mA because, as seen in Figs. h & k, for $I_e=5.0$ mA, the precessions excited by the excitatory pulse are already in the auto-oscillation mode, leading to saturated M_x amplitudes for all subsequent input bit 1 pulses. This leads to the filtered FFT amplitude values being much closer for $I_e=5.0$ mA, causing slightly lower SI as compared to $I_e=3.0$ mA.

Supplementary material 7: Investigation of magnetization dynamics and 4-bit digit pattern separation on modified pulse scheme with $I_e=5.0$ mA, $\delta=1, 20$ & 25 ns, $I_0=1.2$ mA, $I_1=2.4$ mA, $\Delta t=4$ ns, $\tau=3$ ns.

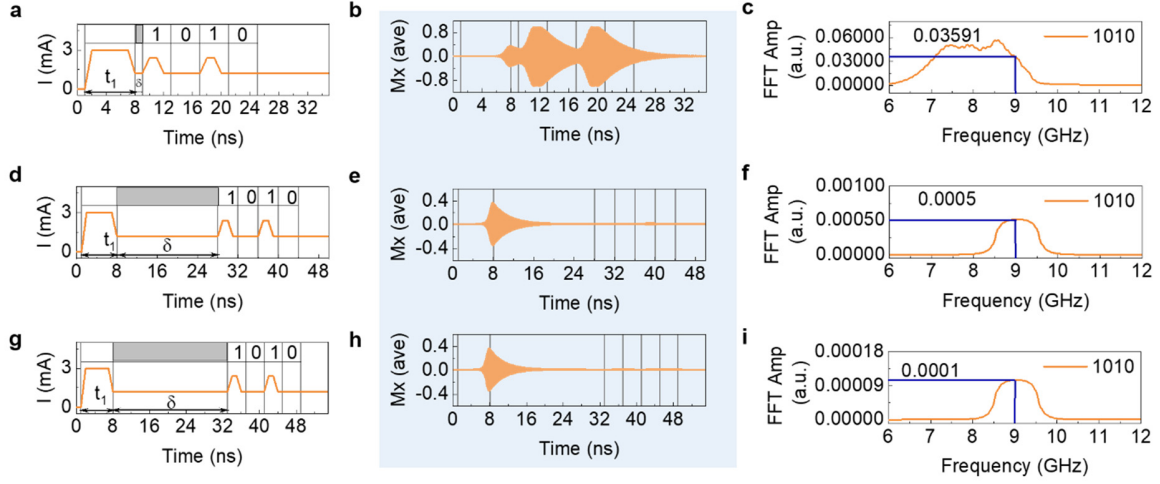


Figure. S7. Figures **a(d,g)**, **b(e,h)** and **c(f,i)** show the 4-bit binary input pulse, corresponding magnetization dynamics and FFT amplitude spectra respectively for the 4-bit pattern 1010 with input parameters $I_e=5.0$ mA, $\delta=1$ ns (20 ns, 25 ns), $I_0=1.2$ mA, $I_1=2.4$ mA, $\Delta t=4$ ns, $\tau=3$ ns. The effect of the excitatory pulse on the input binary pattern decreases with increasing δ . This leads to decreasing M_x amplitudes and therefore decreasing the filtered FFT amplitudes at 9.0 GHz with increasing δ . Moreover, the reduced filtered FFT amplitudes for all 16 combinations of 4-bit input patterns causes the SI to decrease with increasing δ .