Supporting Information for "Anisotropic Magnon-Magnon Coupling in Synthetic Antiferromagnets"

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1. The description of the energy model

For the case when the external magnetic field H is applied in the plane of films, the energy for the system including two identical ferromagnetic layers is[1]

$$E = \sum_{i=1}^{2} d_i [-M_i H cos(\theta_i - \theta_H) - K_u \cos^2 \theta_i] + J_1 \frac{\boldsymbol{M_1} \cdot \boldsymbol{M_2}}{M_1 M_2} + J_2 \left(\frac{\boldsymbol{M_1} \cdot \boldsymbol{M_2}}{M_1 M_2}\right)^2.$$

where $M_1 = M_2 = M_s$ is the magnetization for each CoFeB layer, and d_i (i=1,2) is the thickness for the top and bottom layer, i.e., d_1 is 12 nm and d_2 is 10 nm. K_u is the uniaxial in-plane anisotropy. Its easy axis is defined as the x-axis. θ_i and θ_H are defined as the angle of equilibrium directions for two magnetizations and the external field with respect to the x-axis, respectively. Here, both the so-called bilinear coupling constant J_1 and biquadratic coupling constant J_2 are included. The equilibrium configuration (θ_1 and θ_2) can be obtained through find the minimum of energy. At zero field, if J_1 is positive, the bilinear coupling favors two magnetic layers antiparallel. It is the so-called antiferromagnetic coupling. On other hand, J_2 is positive, the biquadratic coupling favors the two magnetizations 90°-type coupling. More cases have been discussed in ref.[2].

2. The solution of ferromagnetic resonance in SAF

For convenience, we define an effective anisotropy field and effective exchange fields as $H_u=2K_u/M$, $H_{ex1}^{(i)} = \frac{J_{1,i}}{Md_i}$, and $H_{ex2}^{(i)} = J_{2,i}/Md_i$, i=1,2 for the top and bottom magnetic layer, respectively. Based on the coupled Landau-Lifshitz equation (LL), the resonance frequency of magnetization precession can be treated as the solution of the linearized LL equation in the case of a small amplitude of magnetization precession. The dispersion is numerical determined as the eigenvalue of the following matrix:[1]

$$\begin{bmatrix} 0 & H_1 & 0 & H_2 \\ -H_3 & 0 & H_4 & 0 \\ 0 & H_6 & 0 & H_5 \\ H_8 & 0 & -H_7 & 0 \end{bmatrix},$$

where

$$H_1 = H\cos(\theta_1 - \theta_H) + H_u\cos[2(\theta_1 - \theta_u)] + 4\pi M_s + H_{ex1}^{(1)}\cos(\theta_1 - \theta_2)$$

$$- 2H_{ex2}^{(1)}\cos[2(\theta_1 - \theta_2)]$$

$$H_2 = -H_{ex1}^{(2)} + 2H_{ex2}^{(2)}\cos(\theta_1 - \theta_2)$$

$$H_3 = H\cos(\theta_1 - \theta_H) + H_u\cos[2(\theta_1 - \theta_u)] + H_{ex1}^{(1)}\cos(\theta_1 - \theta_2)$$

$$- 2H_{ex2}^{(1)}\cos[2(\theta_1 - \theta_2)]$$

$$H_4 = H_{ex1}^{(2)}\cos(\theta_1 - \theta_2) - 2H_{ex2}^{(2)}\cos[2(\theta_1 - \theta_2)]$$

$$H_5 = H\cos(\theta_2 - \theta_H) + H_u\cos[2(\theta_2 - \theta_u)] + 4\pi M_s + H_{ex1}^{(2)}\cos(\theta_1 - \theta_2)$$

$$- 2H_{ex2}^{(2)}\cos[2(\theta_1 - \theta_2)]$$

$$H_6 = -H_{ex1}^{(1)} + 2H_{ex2}^{(1)}\cos(\theta_1 - \theta_2)$$

$$H_7 = H\cos(\theta_2 - \theta_H) + H_u\cos[2(\theta_2 - \theta_u)] + H_{ex1}^{(2)}\cos(\theta_1 - \theta_2)$$

$$- 2H_{ex1}^{(2)}\cos[2(\theta_1 - \theta_2)]$$

$$H_8 = H_{ex1}^{(1)}\cos(\theta_1 - \theta_2) - 2H_{ex2}^{(1)}\cos[2(\theta_1 - \theta_2)]$$

The eigenvalue is $-i\omega/\gamma = -i2\pi f_r/\gamma$.

3. The FMR spectra for t_{Ir} =1.2 nm at varying θ_H

The ferromagnetic resonance spectra were acquired at varying the magnetic field direction θ_H. Since the anisotropy of the gap is larger in the sample with t_{Ir} =1.2 nm, the spectra for t_{Ir} =1.2 nm is presented in Fig. S1. The red circle curves are calculated based on the parameters from Table I and are also plotted in Fig. S1. At low angles like θ_H=18^o and 30^o (see Fig. S1(a) and (b)), the location of the anticrossing gap closes to the spin-flop field. After spin-flop, the magnetization is not aligned uniformly immediately but after a field window since the broaden distribution of IEC and H_u. It brings the disturbance for counted the gap. Therefore, a significant deviation happens due to this non-uniform.

REFERENCES

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[2] Demokritov S O 1998 Biquadratic interlayer coupling in layered magnetic systems *J. Phys. D: Appl. Phys.* **31** 925–41

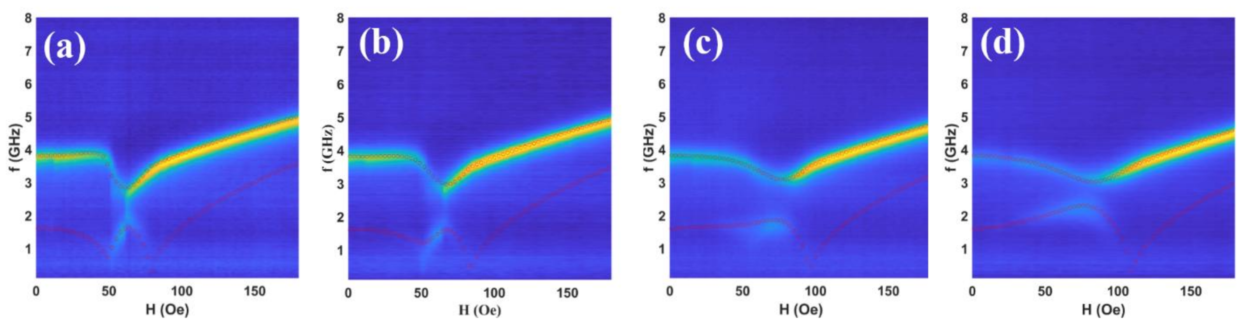

Fig. S1. FMR spectra for CoFeB(10 nm)/Ir(1.2 nm)/CoFeB(13 nm) at varying θ_H, (a) θ_H=18^o, (b), θ_H=30^o, (c) θ_H=45^o, (b), θ_H=70^o, respectively. The red circle curves are calculated based on the parameters from Table I.

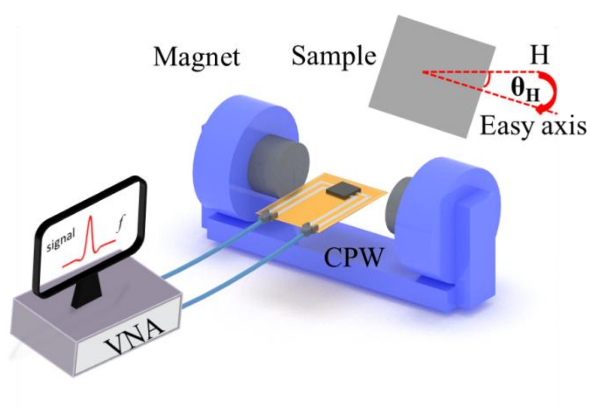

Fig. S2. The illustration of VNA-FMR setup. The sample is rotated in in-plane. θ_H is the angle between its easy axis and the external field.