Direct Detection of Static Dipolar Interaction on a Single Nanodisk Using Microfocused Brillouin Light Scattering Spectroscopy

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1. Introduction

The collective magnetic behavior of a closely-packed disks array is significantly different from the behavior of a single disk. When the inter-disk spacing is considerably smaller than the disk diameter, the magnetization reversal process of the ensemble will be significantly affected by dipolar interaction.\[1-3\] Studying the effect of dipolar interaction between closely-packed disks has become increasingly important in many vital applications such as high density information storage, magnonics crystals, and spin torque nano-oscillators.\[18-22\] So far, these studies were focused on the collective magnetic behavior from an array, \[1,2,23-26\] rather than from a single disk under the influence of neighboring dipolar field. Few reports have investigated the coupled magnetic behavior from a pair of disks.\[27-30\] A dynamic mode profile modification due to static dipolar interaction has been shown to occur within pairs of rectangular nanomagnets using micromagnetic simulations by Dvornik et al.\[30\] Recently, Keatley et al.\[31\] used a time-resolved scanning Kerr microscopy to isolate the dynamic dipolar interaction between a pair of nominally-shaped disks. However, a detailed scrutiny of phase-resolved Kerr ellipticity data is required to determine the dynamic dipolar coupling strength versus edge-to-edge spacing/diameter (s/d) ratio. The effect of dipolar coupling was also found to be inadvertently enhanced due to their fabrication process.

It is essential to perform a systematic investigation on the effect of increasing neighboring static dipolar (henceforth: dipolar) field on a single disk using a precise and straightforward technique. In this paper, we have used a microfocused Brillouin light scattering (BLS) setup to selectively probe the modification in the dynamic behavior of a single disk as a function of increasing dipolar interaction from a neighboring disk. Using pairs of identical disks with varying s, a direct detection of increasing neighboring dipolar field on a single disk is systematically performed. The influence of neighboring dipolar field in modifying the dynamic behavior of the resonant spin waves (SWs) mode is evident in the measured spectra and the 2D mode profiles. In addition, by changing the relative orientation between the inter-disk coupling direction and the applied field, the effect of dipolar interaction on the resonant frequency greatly diminishes when the disks are in a vortex state (at low field). Micromagnetic simulations and analytical calculations are in good agreement with our experimental results. The results and methodology presented in this work are useful in further development of high density magnetic recording media, functional microwave signal processing, and logic devices.

2. Results and Discussions

2.1. Power Linearity Test

Prior to any detailed investigations of the effect of dipolar interaction on a single disk, a preliminary test for microwave power linearity was carried out by sweeping the rf excitation
power (P) in the range from 0.01 to 100 mW (or –20 to 20 dBm) with \( H_{\text{app}} = 1 \) kOe and detecting the BLS photon count of the most prominent mode at \( f = 9.2 \) GHz for the reference isolated disk. This preliminary test is important to ensure that the microwave excitation falls within the linear excitation regime and the dynamic modes are not influenced by or resulting from nonlinear dynamic magnetization.\(^{[33–35]}\) The log–log plot of BLS photon count versus \( P \) shows a linear regime up to 15.85 mW (12 dBm) as shown in Figure 1e. Note that the data for 0.01 mW (–20 dBm) and 0.1 mW (–10 dBm) were not plotted as the power was too low to excite any resonant SWs mode. Based on this plot, the subsequent microwave excitation was carried out with \( P = 10 \) mW (10 dBm), which falls within the linear regime, marked green in Figure 1e.

### 2.2. Effect of Neighboring Dipolar Interaction

#### 2.2.1. BLS Spectra

Figure 2a shows the normalized BLS spectra for the different \( s \) and coupling orientations at \( H_{\text{app}} = 1 \) kOe. Before each measurement, the disks were first saturated with \( H_{\text{app}} = 2 \) kOe. At \( H_{\text{app}} = 1 \) kOe, the disks are in a quasi-saturated single domain state. For each \( s \) (except for the isolated disk), the plots of BLS spectra include the parallel (filled symbols) and perpendicular (open symbols) orientations between the inter-disk coupling direction and \( H_{\text{app}} \). In all measurements, only one excited mode (i.e., mode A) was observed in the disk. The frequency of mode A (\( f_A \)) of the isolated disk (\( s = 500 \) nm) was observed at 9.2 GHz. As \( s \) is reduced, two opposing trends of the change in \( f_A \) were observed between the parallel and perpendicular orientations. In the former, \( f_A \) increases with decreasing \( s \) to \( f_A = 9.5 \) GHz for \( s = 50 \) nm. In the latter, \( f_A \) decreases with decreasing \( s \) to \( f_A = 8.9 \) GHz for \( s = 50 \) nm.

To understand the opposing \( f_A \) trends observed for the different coupling orientations, the nature of neighboring disk dipolar interaction has been analyzed with the aid of Kittel resonance formulation\(^{[36]}\)

\[
f = \frac{\gamma}{2R} \sqrt{\left[H_x + (N_y - N_x)4\pi M_x\right]\left[H_y + (N_z - N_y)4\pi M_z\right]} \tag{1}
\]

where \( N_x, N_y, \) and \( N_z \) are the demagnetizing factors for \( x, y, \) and thickness (\( z \)) directions, respectively, \( \gamma \) is the gyromagnetic ratio of the materials, \( 4\pi M_x \) and \( H_x \) are the magnetization of the sample and the effective field along \( x \) respectively.

In the parallel orientation, where the coupling direction is along \( x \), the dipolar field along \( x \) \( (H_{d,x}) \) adds to \( H_x \) according to the relation: \( H_x = H_{\text{app}} + H_{d,x} \) (see Figure 1d, top panel). Consequently, as the dipolar field magnitude increases with decreasing \( s, f_A \) becomes higher following Equation (1). In the perpendicular orientation, however, \( H_{d,x} \) reduces \( H_x \) according to the relation: \( H_z = H_{\text{app}} - H_{d,z} \). The negative sign marks the
interacting disks with varying metric excitation. In our measurement, pairs of magnetic elements and using asymmetrical measuring the collective response of arrays or out-of-phase (optical) coupled modes, when mode splitting into in-phase (acoustic) and action would typically produce a resonance trends are underlined.

It is important to note that the dipolar interaction would typically produce a resonance mode splitting into in-phase (acoustic) and out-of-phase (optical) coupled modes, when measuring the collective response of arrays or pairs of magnetic elements and using asymmetric excitation. In our measurement, the probing was done on a single disk and not by measuring the collective response of the disks pair. Furthermore, a uniform excitation field generated by the signal line used in our experiment cannot efficiently excite the optical mode for the BLS measurement. Similar observation was reported by Ding et al. [38]

To provide direct evidence of the dipolar interactions, a series of 2D µ-BLS images were acquired from the interacting disks in the parallel orientation with varying $s$ (Figure 2b–d) and isolated disk (Figure 2e) at their respective $f_A$ values. A scan area of 1 $\mu$m $\times$ 1 $\mu$m was used to image the mode profile of the isolated disk while a larger scan area of 1.7 $\mu$m $\times$ 1 $\mu$m was used to image the mode profile of the disks pairs. The scan step used was 50 nm in both $x$ and $y$ directions. The cross-hairs mark the center position of each disk in the scanned image. In the isolated disk, mode A is located at the center of the disk. As $s$ is reduced, mode A is gradually shifted toward the gap region in the disks pair (cf. Figure 2b–d) due to the influence of neighboring dipolar field. For $s = 50$ nm, the mode is strongly shifted toward the edge of the disk. The changing profile of Mode A and the shift of $f_A$ versus $s$ clearly highlight the influence of neighboring dipolar field in modifying the dynamic behavior in a disk.

Here, a methodology to estimate the neighboring dipolar field magnitude on a single disk will be discussed. First, we measured the BLS spectra as a function of $H_{app}$ of the isolated disk (Figure 3a) and disks pair with

2.2.3. Dipolar Field Estimation

2.2.2. 2D µ-BLS Intensity Mapping

Figure 2. a) Plots of normalized BLS spectra for different $s$ and orientations. Plots with filled (open) symbols represent the BLS spectra in the parallel (perpendicular) orientations between the inter-disk coupling direction and $H_{app}$. b–d) 2D µ-BLS images of Mode A at $H_{app} = 1$ kOe for interacting disks with varying $s$. e) 2D µ-BLS images of Mode A at $H_{app} = 1$ kOe for an isolated disk. Color scale bar in e) represents the normalized BLS intensity of the mode profiles in (b–e).

Figure 3. a–c) Normalized 2D BLS spectra versus $H_{app}$ for isolated disk ($s = 500$ nm) and interacting disks with $s = 50$ nm in parallel and perpendicular orientations. d) Plots of calculated $H_d$ and $f_A$ for varying $s$. Color scale bar next to a) represents the normalized intensity of 2D BLS spectra in (a–c).
a particular s, e.g., s = 50 nm (Figure 3b,c) for parallel and perpendicular orientation respectively. From Figure 3a–c, we can distinguish two distinct regions i.e., high field region where the disk is in quasi saturated single domain state and low field region where the disk is in a vortex state. In between these regions, we can also observe abrupt frequency shifts signifying transition between these magnetization states i.e., vortex nucleation and annihilation steps. Second, we fitted the BLS spectra versus $H_{app}$ of the isolated disk for 2000 Oe ≤ $H_{app}$ ≤ 500 Oe using Equation (1) to obtain the demagnetizing factors of the disk. In doing so, we assume that in this field range, the disk remained in quasi-saturated single domain state to give a good fit to Kittel formula. For the case of isolated disk, we assume that no external dipolar field contribution was introduced into the system such that $H_s = H_{app}$. In addition, various fitting parameters and constraints were set as follows (1) $\gamma = 2.8$ GHz / kOe, (2) $M_s = 860$ emu cm$^{-3}$, (3) $N_s = N_y$ (symmetric disk), (4) $N_x + N_y + N_z = 1$ and (5) the tolerance of $N_s$, $N_x$, and $N_z$ was set to be 0.01 for nonideal shape. The fitted demagnetizing factors were found to be $N_s = 0.05$, $N_x = 0.04$, and $N_y = 0.87$. The sum of these demagnetizing factors is equal to 0.97, which is attributed to the 0.01 tolerance of each demagnetizing factor. Finally, using the demagnetizing factors obtained, the dipolar field in the disks pair was determined by fitting the measured BLS spectra within the same $H_{app}$ range but using a modified $H_s = H_{app} + H_{d-x}$ expression (as discussed earlier) into Equation (1). The fitted dipolar field obtained is $H_{d-x} = 85 \pm 5$ Oe with s = 50 nm in the parallel orientation. Using the same $H_s = H_{app} + H_{d-x}$ expression to fit for the dipolar field in disks pair with s = 50 nm in the perpendicular orientation gives $H_{d-x} = -58 \pm 7$ Oe. The negative $H_{d-x}$ confirms the legitimacy of the model of dipolar field orientation presented earlier based on Figure 1d. In addition, the smaller $|H_{d-x}|$ value obtained in the perpendicular orientation indicates a larger effective distance between magnetic poles of the neighboring disks in this orientation. However, this was not obvious when comparing the $\Delta H_s$ values at $H_{app} = 1$ kOe for the disk with s = 50 nm in different orientations i.e., both orientations give the same $\Delta H_s = 0.3$ GHz.

Using the same demagnetizing factors obtained, it is possible to calculate the $f_s$ values with $H_{app} = 1$ kOe for varying s by assuming the dipolar field of the neighboring disk $H_d(r)$ according to Equation (2)

$$H_d(r) = 2 \left[ \frac{m}{r} \right]$$

(2)

The $H_d(r)$ expression is obtained by approximating the neighboring disk as a current loop,[39] where $m$ is the total magnetic moment of the neighboring disk in emu and $r = s + d$ is the center-to-center distance between disks in a disks pair for different s. Accordingly, the $f_s$ values could be calculated using Equation (1) with the modified expression $H_s = H_{app} + H_d(r)$.

Figure 3d plots the calculated $H_d$ and the corresponding $f_s$ values versus s. It is important to note that using Equation (2), there is a small magnitude of dipolar field $H_d = 20$ Oe calculated for s = 500 nm. The corresponding calculated $f_s$ value for s = 500 nm is 8.65 GHz, which is smaller than in the experiment (i.e., 9.2 GHz). The difference between the measured and the estimated $f_s$ may come from the nonideal demagnetizing factors and assumption of uniform M inside the disk used in the calculation. For s = 50 nm, the $H_d$ is estimated to be 312 Oe, which is much larger than the $H_d$ fitted experimentally. The overestimation is due to the assumption of fully saturated single domain state in the disk in the calculation which may not the case in the experiment at $H_{app} = 1$ kOe. The corresponding calculated $f_s$ and $\Delta f_s$ are 10.05 and +1.40 GHz respectively between s = 500 and s = 50 nm. The calculated $\Delta f_s$ is much larger than the experimental $\Delta f_s$ due to the significant increase in the calculated $H_d$ with reducing s by a factor of $(s + d)^{-3}$ in Equation (2). If the $H_d$ was assumed to be 105 Oe i.e., by adding the value of $H_{d-x} = 85$ Oe fitted earlier to the nonzero $H_d = 20$ Oe calculated for s = 500 nm, the $f_s$ is calculated to be 9.08 GHz. The corresponding $\Delta f_s$ becomes +0.43 GHz which is much closer value to the experimental $\Delta f_s = +0.3$ GHz.

### 2.2.4. Micromagnetic Simulations

In order to provide a comprehensive understanding of the static reversal mechanism and dynamic behavior of the disks, a series of micromagnetic simulations were performed using object-oriented micromagnetic modeling framework (OOMMF).[40]

The saturation magnetization was taken as $M_{s,NiFe} = 860$ emu cm$^{-3}$, exchange constant $A_{NiFe} = 13 \times 10^{-7}$ erg cm$^{-1}$, and magnetocrystalline anisotropy $K_{1,NiFe} = 0$. The uniaxial anisotropy of the NiFe was assumed to be negligible when compared with the shape anisotropy of the patterned structures. A unit cell size of $5 \times 5 \times 5$ nm was used in the simulations. The masks used in the simulations were extracted from scanning electron microscopy (SEM) images of the fabricated structures. For quasi-static simulation, a damping coefficient of $\alpha = 0.5$ was chosen to obtain a rapid convergence. To simulate the BLS response and quantify the spatial characteristics of SWs mode, time-dependent simulations were performed using a gyromagnetic ratio $\gamma = 2.8$ GHz / kOe and $\alpha = 0.008$. A time-varying sinc wave excitation field $h_{exc} = h_0 \frac{\sin(2\pi ft)}{t}$ was used to simulate the BLS response in the disks, where $h_0 = 50$ Oe was set as the initial amplitude of the sinc wave. The sinc wave was used in the simulation to yield a uniform excitation in the frequency domain. The use of $h_0 = 50$ Oe falls within linear excitation regime in the simulation. This is confirmed by the same simulated mode profile which was produced using a smaller $h_0 = 2$ Oe. The dynamic simulation results were analyzed in the frequency domain by performing Fast Fourier Transform (FFT) processing.

The simulated hysteresis loops for the isolated disk (s = 500 nm) and interacting disks with s = 50 nm (both orientations) are shown in Figure S1 (Supporting Information). In all cases, the hysteresis shows two switching steps corresponding to the vortex nucleation and annihilation in the disk. The corresponding switching fields were determined by taking the first derivative of the $M$–$H$ loop in the backward sweep direction. The derivative curves were plotted together with the $M$–$H$ loop and the switching fields were marked by the arrows. The simulated nucleation field ($H_{n}$) and annihilation field ($H_{a}$) for the isolated disk are 0 and $-700$ Oe, respectively. For s = 50 nm,
the $H_N$ and $H_A$ are $-100$ and $-600$ Oe for parallel orientation and $100$ and $-700$ Oe for the perpendicular orientation, respectively. In the experiment (see Figure 3a–c), the switching field can be determined by the region where abrupt frequency shifts occur. Comparing the simulated hysteresis loops to the 2D BLS spectra in Figure 3a–c, we can infer that the transition region, where multiple peaks were observed corresponds to the disk having a vortex state. The experimental $H_N$ and $H_A$ for the isolated disk are 175 and $-500$ Oe. For $s = 50$ nm, the experimental $H_N$ and $H_A$ are 100 and $-400$ Oe for parallel orientation and 175 and $-500$ Oe for perpendicular orientation, respectively. The switching field values in the simulations are larger than in the experiments. This may arise due to the absolute 0 Kelvin temperature used in the simulation.

Although the switching field values are different between the experiments and simulations, the trends are similar. For instance, the $H_N$ for disks with $s = 50$ nm in parallel orientation is smaller than that for isolated disk in both simulation and experiment. This is due to the additional dipolar field which stabilizes the single domain state and causes the formation of vortex state to occur at a smaller field. For vortex annihilation, a larger $H_A$ is required for disks with $s = 50$ nm in parallel orientation than for the isolated disk due to the enhanced dipolar interaction at the edge of the disk as the vortex annihilates to form a single domain state. In the perpendicular orientation, the $H_N$ and $H_A$ values for disks with $s = 50$ nm is similar to the isolated disk in both simulation and experiment due to a significantly reduced dipolar interaction between disks.

Figure 4a shows the normalized simulated frequency response for different $s$ and orientations at $H_{app} = 1$ kOe. At $H_{app} = 1$ kOe, the disks are in a quasi-saturated single domain state. Similar to the plot in Figure 2a, for each $s$ (except for the isolated disk), the plots of simulated spectra include the parallel (filled symbols) and perpendicular (open symbols) orientations between the inter-disk coupling direction and $H_{app}$. Similar to the experiments, only one mode A was observed in the disk at this field in the simulations. The $f_A$ of the isolated disk ($s = 500$ nm) was observed at 9.18 GHz, which is very similar to the $f_A$ in experiment. Again, the two opposing trends of $f_A$ change were observed between the parallel and perpendicular orientations as $s$ is reduced in agreement with our experimental observations. In the parallel orientation, $f_A$ increases with decreasing $s$ to $f_A = 9.77$ GHz for $s = 50$ nm ($\Delta f_A = 0.59$ GHz). In the perpendicular orientation, $f_A$ decreases with decreasing $s$ to $f_A = 8.9$ GHz for $s = 50$ nm ($\Delta f_A = 0.59$ GHz). The $|\Delta f_A|$ in simulations is twice as large as $|\Delta f_A|$ in experiments. A larger $|\Delta f_A|$ could indicate a stronger influence of dipolar field in modifying the magnetization dynamics in simulation (partly due to the 0 Kelvin assumption) than in experiment. This argument is supported by the fact that the $f_A$ values for the isolated disk (i.e., no neighboring dipolar field) in both experiment and simulated are very close to one another. The frequency splitting is not observed in our simulation as a uniform sinc wave excitation was used and it could not efficiently excite the optical mode.[30]

The corresponding mode A’s profiles for the interacting disks with varying $s$ and orientations are shown in Figure 4b–j. Similar to the experiment, the isolated disk in the simulation has an intense mode A’s intensity at its center. As $s$ is reduced in parallel orientation, mode A shifts toward the gap region between the disks due to dipolar interaction similar to the experiment. For $s = 50$ nm, mode A is strongly shifted to the disk’s edge with an apparent intensity ripple toward the gap region.

**Figure 4.** a) Plots of normalized simulated resonant frequency spectra for different $s$ and orientations. Plots with filled (open) symbols represent the simulated spectra in the parallel (perpendicular) orientations between the inter-disk coupling direction and $H_{app}$ b–e, g–j. Simulated Mode A profiles at $H_{app} = 1$ kOe for interacting disks with varying $s$ in parallel and perpendicular orientations. f) Simulated Mode A profile at $H_{app} = 1$ kOe for an isolated disk. Color scale bar next to (f) represents the normalized FFT intensity of the mode profiles in (b–j).
is due to the strong dipolar interaction from the neighboring disk at $s = 50$ nm. The shifted mode A profile may have caused a stronger dynamic interaction between the neighboring disk and the disk under test resulting in the intensity ripple of Mode A toward the gap region. The convolution of the intensity ripple in the mode profile and the Gaussian profile of the probing laser spot may be a factor which makes this intensity ripple difficult to be resolved in the experimental 2D μ-BLS images for small $s$. In contrast, mode A in the disks with perpendicular orientation seems to be unaffected by the reduction in $s$ along the coupling direction. The effect of reducing $s$ is evident only for $s \leq 100$ nm (Figure 4g,h) where mode A is offset along x (in opposite direction for each disk).

To estimate the magnitude of neighboring dipolar interaction on a disk, first we extracted the $H_{d,x}$ values from the static simulation at $H_{app} = 1$ kOe as shown in Figure S2a–e (Supporting Information). Second, we obtained the $H_{d,x}$ values along the line $a-a'$ from Figure S2a–e (Supporting Information) and plotted them in Figure S2k (Supporting Information). Finally, we determined the $H_{d,x}$ values in the gap region for different $s$. We observed that $H_{d,x}$ increases largely from $H_{d,x} = 0.54$ kOe for $s = 200$ nm to $H_{d,x} = 3.58$ kOe for $s = 50$ nm. In comparison, the simulated $H_{d,x}$ value for $s = 25$ nm and $s = 100$ nm away from the isolated disk’s edge are 1.56 and 0.35 kOe, respectively, which are much smaller than in the case of interacting disks with the same $s$. It is evident from this comparison that the presence of neighboring disk in a single domain state largely increases the $H_{d,x}$ magnitude which adds to the total internal field of the disk under test. The increase of $H_{d,x}$ as $s$ is reduced modifies the internal field near the region between the interacting disks and leads to the observed shift in the profile of Mode A.

It is important to note that the edge mode is not observed in both experiment and simulation at $H_{app} = 1$ kOe in all measurements. The edge mode is still not observed even when applying the maximum possible $H_{app} = 2$ kOe in our experimental setup. Similarly, simulation with $H_{app} = 2$ kOe shows only the center Mode A. It is likely that a much larger $H_{app}$ is required before the edge mode can be observed in $d = 500$ nm disk. This is confirmed with the simulation using $H_{app} = 5$ kOe which shows both center and edge modes. This is unlike the case of $d = 300$ nm circular disk, where an edge mode is observed with $H_{app}$ as low as 0.25 kOe\(^{[41]}\).

### 2.3. Vortex State Disks

Next, we present the BLS response of the disk at remanence. **Figure 5** plots the BLS spectra at remanence for isolated disk ($s = 500$ nm) and interacting disks with $s = 50$ nm in parallel (filled diamond symbols) and perpendicular (open diamond symbols) orientations.

![Figure 5](https://www.wileyonlinelibrary.com)  
**Figure 5.** Plots of normalized BLS spectra for isolated disk ($s = 500$ nm) and interacting disks with $s = 50$ nm in parallel (filled diamond symbols) and perpendicular (open diamond symbols) orientations.

In order to understand the origin of the multiple modes observed at remanence, we performed dynamic simulations for both the isolated disk and interacting disks of varying $s$. We made a reasonable assumption that all the disks are in a vortex state. For disk pair with $s = 50$ nm, the simulations for both coupling orientations were performed. **Figure 6a** plots the simulated frequency response at remanence when the disks are in the vortex state. In agreement with the measured BLS spectra, there are two peaks observed at the lower frequencies and two weaker peaks at higher frequencies. Interestingly, there is no noticeable change in the peak as a function of $s$ and orientations. The peak values are $7.23, 8.79, 11.52$, and $12.5$ GHz which are labeled as Mode B, C, D, and E, respectively. The formation of vortex state results in the minimization of the dipolar field emanating from the neighboring disk.

**Figure 6b** shows the simulated mode profiles of each mode. As the disks are in the vortex state, which contains the circumferential magnetization in-plane (IP) and the vortex core pointing out-of-plane (OP), it is important to extract both the IP and OP components of the mode profiles. For the disk in vortex state, the SWs mode can be labeled using two numbers $n$ and $m$ according to the number of radial and azimuthal modes respectively\[^{[42,43]}\]. As the name suggests, the radial modes has their nodes along the radius while the azimuthal modes has their nodes along the circumference of the disk. The observed modes are characterized according to the notation $(n, m)$ as follow: Mode B and C are the azimuthal modes $(0, 3)$ and $(0, 4)$ centered on the vortex core respectively, Mode D is the radial mode $(1, 0)$, and finally Mode E is the mixed mode $(2, 1)$. The symmetry nodes are not very sharp and possibly overlapping with other modes having the same $j$ but different wave vector $k$.\[^{[44]}\] Mode E is very similar to the mode profile observed in a much larger disk observed...
the simulated spectra in the parallel (perpendicular) orientations between the inter-disk coupling direction and intensity of the mode profiles in (b).

Figure S2, [cf. (a–e), (f–j) (Supporting Information)] clearly show a large reduction of frequencies and mode profiles are not significantly affected by the variation in s. The mode profiles remains centered on the disk regardless of the s value. The simulated $H_{d}$ plots in Figure S2, [cf. (a–e), (f–j) (Supporting Information)] clearly show a large reduction of $H_{d}$ values when the disks are in the vortex state compared with when they are in a quasi-saturated single domain state. Note the scale difference in the $H_{d}$ plots between the two magnetization states (insets in Figure S2a,f, Supporting Information).

The simulated spectra for s = 100, 150, and 200 nm are available in Figure S3, Supporting Information. When the disks are in the vortex state, both the resonant frequencies and mode profiles are not significantly affected by the variation in s. The mode profiles remains centered on the disk regardless of the s value. The simulated $H_{d}$ plots in Figure S2, [cf. (a–e), (f–j) (Supporting Information)] clearly show a large reduction of $H_{d}$ values when the disks are in the vortex state compared with when they are in a quasi-saturated single domain state. Note the scale difference in the $H_{d}$ plots between the two magnetization states (insets in Figure S2a,f, Supporting Information).

3. Conclusion

In conclusion, we have shown the direct detection of the neighboring dipolar interaction on a single disk using micro-focused BLS spectroscopy. By systematically varying the spacing between a disk under test and the neighboring disk, the effect of increasing neighboring dipolar field on the dynamic behavior of a single disk is investigated. When the disk is in a single domain state, the dipolar interaction was found to be highly anisotropic between the parallel and perpendicular orientation of the inter-disk coupling direction with respect to the $H_{\text{app}}$ direction. For instance, two opposing trends in the resonant frequency values change versus s were observed. Two different modes of dipolar interaction were found to be responsible for these opposing trends. Furthermore, in the parallel orientation, decreasing the inter-element spacing was found to strongly shift the resonant mode profiles toward the gap region. This is unlike the case of perpendicular orientation in which decreasing the inter-element spacing only weakly modifies the resonant mode profiles. Clear evidence of the influence of neighboring dipolar field on the dynamic behavior of the resonant mode is seen in the measured BLS spectra and 2D mode profile scans. In addition, we demonstrated an approach to accurately quantify the magnitude of neighboring dipolar field on a single disk. Finally, by comparing the dynamic behavior of the interacting disks in a single domain state and a vortex state, the effect of dipolar interaction was clearly distinguished. In particular, the measured BLS spectra and 2D mode profile scans of the interacting disks in a vortex state are not affected by the changing s. The formation of vortex state has minimized the magnitude of dipolar field emanating from the disk’s boundary due to its flux-closure magnetization. These results and the methodology discussed in this paper may find useful applications in magnetic based devices such as in the design of high density magnetic recording media, functional microwave signal processing and logic devices.

4. Experimental Section

To excite the dynamic modes in the disks, a shorted ground-signal-ground (GSG) coplanar waveguide (CPW) made up of Cr(3 nm)/Pt(200 nm)
was first fabricated on a SiO2/Si substrate using the UV lithography and liftoff process, see schematic in Figure 1a. The Cr adhesion layer was deposited using electron beam evaporation at a rate of 0.2 Å s⁻¹ while the Pt layer was deposited using sputter deposition at a rate of 0.39 Å s⁻¹. These deposition steps were done successively without breaking the chamber’s vacuum. The deposition chamber has a base pressure of 4 × 10⁻⁸ Torr. Subsequently, a range of Ni80Fe20 (NiFe) disks pairs (d = 500 nm, thickness t = 25 nm) with different s (nm) {s = 200, 150, 100, 50} and orientations were patterned using electron beam lithography directly on the signal line of the shorted CPW, see inset of Figure 1a. A reference isolated disks array with s = 500 nm was also fabricated in this process. The NiFe layer was deposited using electron beam evaporation at a rate of 0.2 Å s⁻¹ followed by a lift-off process. Successful lift-off was confirmed using scanning electron microscopy (SEM). Figure 1b–c show examples of high quality disks with s = 500 and s = 50 nm in the parallel orientation with the coordinate axes labeled. The schematic diagrams in Figure 1d compares the two coupling configurations of the fabricated disks pair (parallel and perpendicular to the microwave signal line).

To excite and detect the resonant SWs modes in the disks, a combination of continuous microwave excitation and a laser probing technique was used. The microwave excitation was produced by a signal generator through the shorted CPW using a C–S–G-type microwave coplanar probe. A laser with 250 nm spot size was used to detect the dynamic response of a single disk (inset of Figure 1a). The sample was positioned such that the signal line is oriented along the Happ and the generated radio-frequency microwave field (hμ) is perpendicular to the Happ as shown in Figure 1a.

Supporting Information
Supporting Information is available from the Wiley Online Library or from the author.

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