


 Cite this: *Nanoscale*, 2024, **16**, 4858

## Tunable 2-D magnonic crystals: effect of packing density

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Magnonic crystals, periodic arrays of magnetic structures, have emerged as a promising platform for manipulating and controlling spin waves in magnetic materials. Magnetic antidot nanostructures, representing 2-D magnonic crystals, are versatile platforms for controlling and manipulating magnons. In this work, we systematically investigate the effects of inter-hole spacing and lattice (rhombic and honeycomb) arrangements on the dynamic properties of Ni<sub>80</sub>Fe<sub>20</sub> antidot structures. The dynamic responses of antidot lattices of fixed hole diameter ( $d = 280$  nm) and inter-hole spacing ( $s$ ) between 90 and 345 nm are investigated using broadband ferromagnetic spectroscopy. Multiple resonance modes sensitive to  $s$  are observed due to the inhomogeneous internal field distribution induced by the presence of holes. There is a marked variation in mode frequency, mode intensity and the number of modes for rhombic antidot lattice as the inter-hole spacing and applied field direction are varied. Our experimental results are in good agreement with micromagnetic simulations. Our findings may find application in the design of magnonic-based devices.

 Received 3rd November 2023,  
 Accepted 26th January 2024

DOI: 10.1039/d3nr05582e

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## Introduction

Magnonic crystals (MCs) are periodic arrays of magnetic structures that exhibit unique magnonic properties, including band gaps and tailored spin wave dispersion relations.<sup>1–3</sup> These periodic magnetic structures have garnered considerable attention due to their ability to control and manipulate spin waves or magnons.<sup>4</sup> In this context, magnetic antidot nanostructures, representing 2-D MCs, are versatile platforms for controlling and manipulating magnons.<sup>5</sup> The Spin wave (SW) modes and the magnonic band structure of antidot lattice can be tailored by varying the lattice symmetry,<sup>6</sup> lattice constant,<sup>7</sup> size and shape of the holes,<sup>8,9</sup> and orientation of the magnetic field.<sup>10–15</sup> The SW modes in antidot lattices exhibit a significant anisotropy induced by the lattice symmetry of the holes.<sup>16</sup> Field orientation and strength can control standing and propagating SWs in a square antidot lattice.<sup>17</sup> Significant effects of geometrical parameters of the square antidot lattice on SW modes and the formation of magnonic minibands have been observed.<sup>7,10,18,19</sup>

The magnetic properties of antidot structures with square lattice are extensively studied by varying the applied field orientation and strength,<sup>17</sup> hole diameter,<sup>10</sup> inter-hole spacing,<sup>7</sup> thickness,<sup>19</sup> and hole shape.<sup>20</sup> There are fewer

reports in the literature on the experimental investigation of the effects of geometrical parameters on the magnetic properties of rhombic and honeycomb antidot lattices.<sup>12</sup>

In this study, we systematically investigated the dynamic behaviors displayed by rhombic and honeycomb Ni<sub>80</sub>Fe<sub>20</sub> (permalloy, Py) antidots characterized by a fixed diameter ( $d = 280$  nm) and varying inter-hole spacing ( $s$ ) within the range of 90 nm to 345 nm. We observed that the FMR responses of antidot structures are highly sensitive to the  $s$  and  $H_{\text{app}}$  directions. Antidot lattices exhibit a significant tunability of the number of observed modes and mode frequency, which can be tailored by varying  $s$  and  $H_{\text{app}}$  directions.

## Experimental details

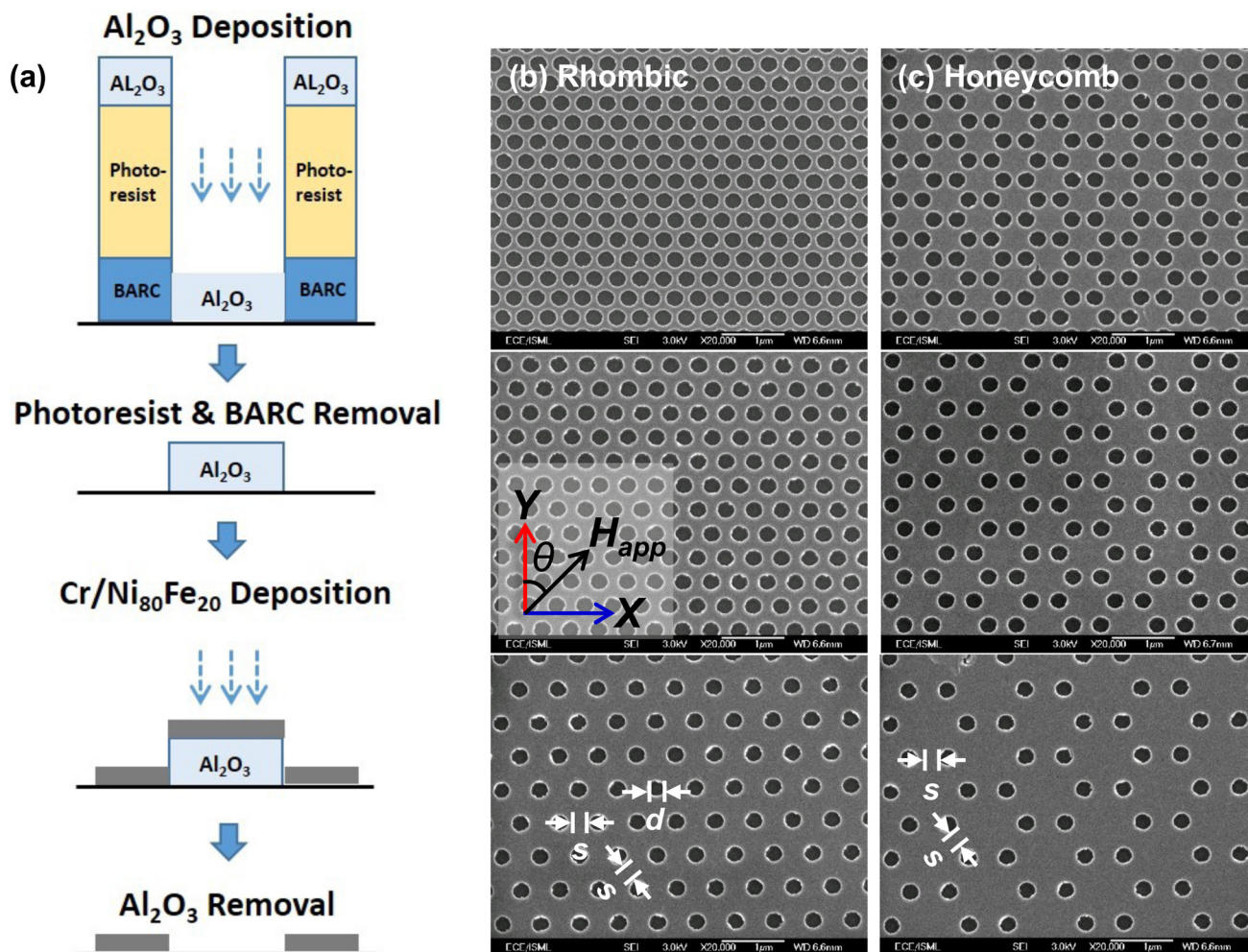
### Sample fabrication

Periodic arrays of circular holes arranged in rhombic and honeycomb lattices were patterned in a resist film on Si substrate using deep ultraviolet lithography at 248 nm exposure wavelength. Details of the resist pattern fabrication process were described previously.<sup>21</sup> In the first step, a 65 nm thick Al<sub>2</sub>O<sub>3</sub> layer was deposited by electron beam evaporation followed by a lift-off process. Subsequently, Cr (5 nm)/Py (25 nm) films were deposited on top of the patterned Al<sub>2</sub>O<sub>3</sub> (65 nm) dots using electron beam evaporation at a rate of 0.2 Å s<sup>−1</sup>. The Al<sub>2</sub>O<sub>3</sub> layer was selectively removed using AZ 300 MIF standard developer in the final step. This step removed the Al<sub>2</sub>O<sub>3</sub> layer with the Cr (5 nm)/Py (25 nm) above it, resulting in Py antidot

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**Fig. 1** (a) Schematic diagram of the fabrication process from resist hole patterns. (b) SEM images of 25 nm thick permalloy antidot structures of hole diameter  $d = 280$  nm with inter-hole spacing  $s = 90, 170$ , and  $345$  nm for (a) rhombic, (b) square and (c) honeycomb lattices.

structures. Fig. 1(a) shows a schematic diagram of the fabrication processes from resist holes. Fig. 1(b and c) shows the scanning electron micrographs (SEM) of antidot structures ( $d = 280$  nm) of the rhombic and honeycomb lattices. The spacing between the nearest neighbor holes along the  $X$  direction varies from 90 nm to 345 nm. The SEM images show highly ordered nanoscale antidot lattices with good uniformity. The direction of the external magnetic field  $H_{\text{app}}$  is denoted by an angle  $\theta$  from the  $+Y$  direction, as indicated as an insert in Fig. 1(b). To obtain the high-frequency response, an on-chip integrated coplanar waveguide (CPW) made up of  $\text{Al}_2\text{O}_3$  (50 nm)/Cr (5 nm)/Pt (200 nm) was fabricated on top of the antidot structures using standard optical lithography and lift-off process. All the thin film depositions were done in a vacuum chamber with a base pressure of  $4 \times 10^{-8}$  Torr.

### FMR measurements

The dynamic responses of the antidot structures were characterized using broadband ferromagnetic resonance spectroscopy with a vector network analyzer (VNA), which was con-

nected *via* two G-S-G-type microwave probes to the on-chip CPW. The FMR measurements were performed at room temperature by sweeping the frequency from 100 MHz to 20 GHz for a given  $H_{\text{app}}$ . A reference background signal measured was subtracted from the FMR spectrum. In our investigation, we concentrated on the saturation region at  $H_{\text{app}} = -1400$  Oe. This choice was motivated by the fact that magnetic states in this region are uniform and well-defined, enabling meaningful comparative studies of the antidot lattices (rhombic and honeycomb).

### Simulations details

Micromagnetic simulations were performed using NIST's object-oriented micromagnetic framework (OOMMF) code.<sup>22</sup> The following standard material parameters were used for Py, namely: saturation magnetization  $M_{\text{s,Py}} = 860$  emu  $\text{cm}^{-3}$ , exchange constant  $A_{\text{Py}} = 13 \times 10^{-7}$  erg  $\text{cm}^{-1}$ , and magnetocrystalline anisotropy  $K_{1,\text{Py}} = 0$  erg  $\text{cm}^{-3}$ . The magnetocrystalline anisotropies of the bulk Py film were assumed to be negligible compared to the shape anisotropy of the patterned structures.



A unit cell size of  $5 \times 5 \times 5 \text{ nm}^3$  was used in simulations. Time-dependent simulations were performed using a sinc wave excitation field  $h_{\text{sinc}} = h_0 \frac{\sin(2\pi ft)}{t}$ , where  $h_0 = 50 \text{ Oe}$ , with a gyromagnetic ratio  $\frac{\gamma}{2\pi} = 2.8 \text{ GHz kOe}^{-1}$  and a damping coefficient of  $\alpha = 0.008$ . 2-D periodic boundary conditions were employed in these simulations to simulate the FMR response. The sinc wave was used in the simulation to yield a uniform excitation in the frequency domain. The dynamic simulation results were analyzed in the frequency domain after Fast Fourier Transform (FFT) processing.

## Results and discussion

### Rhombic antidot lattices

Fig. 2(a) shows the normalized experimental FMR absorption spectra of rhombic antidot lattices taken at  $H_{\text{app}} = -1400 \text{ Oe}$  applied along the  $X$  and  $Y$  directions for  $d = 280 \text{ nm}$  as a function of  $s$ . We observed that the FMR response is very sensitive to the inter-hole spacing  $s$ . A change in  $s$  results in a shift of mode frequency and a variation in mode number and inten-

sity. For  $s = 90 \text{ nm}$ , we observed two prominent modes (R1 at  $9.5 \text{ GHz}$ , R4 at  $14.9 \text{ GHz}$ ) and two minor modes (R2 at  $11.6 \text{ GHz}$ , R3 at  $12.8 \text{ GHz}$ ). The multiple resonance modes observed may be attributed to the inhomogeneous internal field distribution induced by the presence of holes.<sup>16</sup> For  $s = 170 \text{ nm}$ , we observed five modes (R1, R2–5) and found the frequency of prominent mode R1 ( $f_{\text{R1}}$ ) increases to  $10.4 \text{ GHz}$ . For  $s = 345 \text{ nm}$ , only three main modes (R1', R1 and R4) and a satellite mode at  $11.7 \text{ GHz}$  are observed, and  $f_{\text{R1}}$  is further increased to  $11.2 \text{ GHz}$ . The corresponding experimental FMR spectra of rhombic antidot lattices for the  $H_{\text{app}}$  applied along the  $Y$  direction as a function of  $s$  are significantly modified, as shown in Fig. 2(a). The significant difference in the FMR spectra between  $H_{\text{app}}$  along  $X$  and  $Y$  directions for the range of  $s$  investigated is attributed to the induced configurational anisotropy of the lattice symmetry.

We have performed a series of dynamic simulations to understand further the origin of the complex FMR spectra observed. Fig. 2(b) shows the corresponding simulated FMR spectra of rhombic antidot lattices as a function of  $s$  for  $H_{\text{app}}$  along the  $X$  direction. There is a good agreement between the experimental results (Fig. 2(a)) and simulated FMR spectra. We

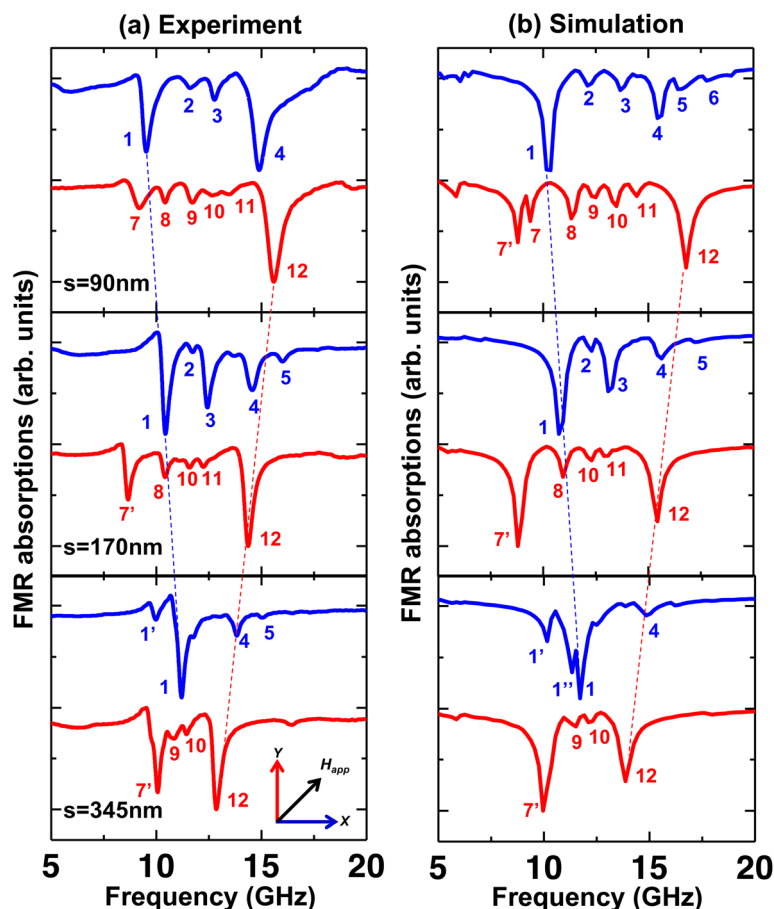


Fig. 2 (a) Experimental and (b) Simulated FMR spectra of 25 nm thick permalloy rhombic antidot lattices as a function of  $s$  taken at  $H_{\text{app}} = -1400 \text{ Oe}$  along the  $X$  and  $Y$  directions.

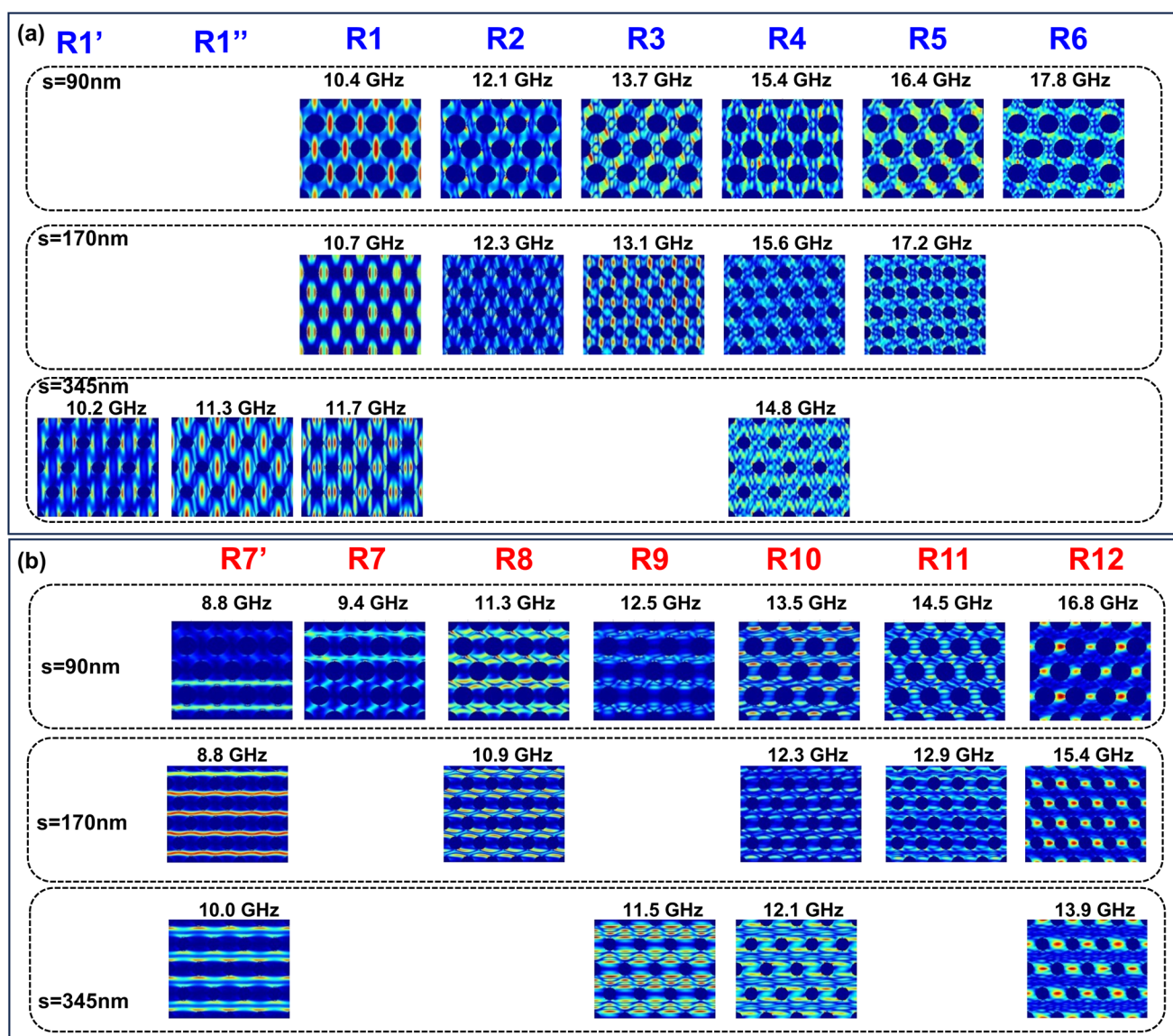




have extracted the mode profile by performing FFT on in-plane magnetization components ( $m_x$ ) to identify the FMR modes. We have plotted the profiles for the observed modes for rhombic antidot lattices for  $H_{\text{app}}$  applied along the X-direction in Fig. 3(a) as a function of  $s$ . The simulated FMR spectrum of  $s = 90$  nm identifies six distinct modes that reside along the Y-direction. We found that mode R1 is enclosed between two next-nearest neighbor holes in the same column, while modes R(2–6) are localized between the two nearest-neighbor holes. Mode R4 shows a stripe-like profile which connects two nearest-neighbor holes. Modes (R2, R3, R5, R6) show a blade-shaped profile with a strong spin precession amplitude at the edges of holes. Instead of three modes R(4–6) found in the simulation, we only observed one shoulder of mode R4 in the experiment, which may be attributed to the fact that modes (R5, R6) are too weak to be resolved in the experiment.

For  $s = 170$  nm, mode R1 shows a profile similar to  $s = 90$  nm but with a large amplitude near the hole edges. However, we observed that the R3 mode intensifies while the R2 mode weakens but persists in both the experimental and simulated data.

For  $s = 345$  nm, however, fewer modes are observed. Instead of a single peak of mode R1 observed in the experiment, we found a dual peak with very close frequencies in the simulation. Mode R1 for  $s = 345$  nm shows a very similar profile to that for  $s = 90$  nm. We also noticed a satellite mode R1', which resides along the Y direction, close to the hole edges. This may be attributed to the increasingly inhomogeneous magnetization near the edges of the holes when  $s/d$  is larger. It is possible to qualitatively understand the decrease in observed mode number as  $s$  is increased since the FMR responses of the antidot structures resemble that of the continuous unpat-



**Fig. 3** Spatial profiles of modes in the simulated FMR spectra taken at  $H_{\text{app}} = -1400$  Oe along (a) X and (b) Y directions of 25 nm thick permalloy rhombic antidot lattices as a function of  $s$ .



terned film, which has a single FMR mode with a resonance frequency  $f_{\text{cont}} = 11.2$  GHz in our reference film. This is similar to the frequency of mode R1 at  $f_{\text{cont}} = 11.2$  GHz for  $s = 345$  nm.

The corresponding simulated FMR spectra of rhombic antidot lattices for the  $H_{\text{app}}$  applied along the  $Y$  direction as a function of  $s$  are shown in Fig. 2(b). The significant difference in the FMR spectra between  $H_{\text{app}}$  along  $X$  and  $Y$  directions for the range of  $s$  investigated is attributed to the induced configurational anisotropy of the lattice symmetry.

We have also extracted the profiles for the observed modes identified in Fig. 3(b) as a function of  $s$ . When  $H_{\text{app}}$  is applied along the  $Y$  direction, these observed modes reside along  $X$ . In the simulation, the excitation field  $h_{\text{sinc}}$ , represented by a sinc wave, is applied perpendicular to the  $H_{\text{app}}$ . This configuration effectively stimulates the magnetization perpendicular to the  $h_{\text{sinc}}$  direction, mimicking the actual experimental conditions.

For  $s = 90$  nm, we found that mode R7 is localized in the area between rows of holes while mode R12 is localized between two nearest-neighbor holes of the same row. In the simulation, mode R7 is a dual peak with very close frequencies, labelled modes R7 and R7'. They display complementary spatial profiles due to a local variation in the dynamic magnetization, which is sensitive to the simulation. This dual peak manifests itself as a single peak in the experiment. Other minor modes R(8–11) show complicated spatial profiles, mainly located between rows of holes, because of hybridization effects with the higher frequency mode.<sup>16</sup>

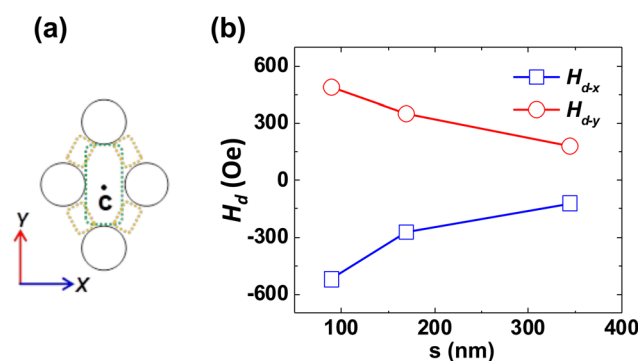
For  $s = 170$  nm, we found that the intensity of mode R7 becomes more pronounced than  $s = 90$  nm, which was also confirmed in the experiment. We did not observe mode R9, probably because it is too weak to be identified. For  $s = 345$  nm, the intensity of mode R7 is further increased, and it is confirmed in the simulation. The profile of mode R7 for  $s = 345$  nm shows a symmetry node in the middle region between rows of holes with a peak amplitude near the holes' edges. This is quite different when compared with the profile of mode R7 for  $s = 90$  and  $170$  nm. The increase in the intensity of mode R7 as  $s$  is increased can be explained by considering its resonance area, which is extended in the area between rows of holes. When  $s$  is increased, the contribution from this area is increased due to more materials (increasing the width of the resonant area), so mode R7 becomes more pronounced. Interestingly, fewer modes are identified for  $s = 345$  nm, probably because different modes combined or are too weak to be observed.

For  $H_{\text{app}}$  along the  $X$  and  $Y$  directions, we will discuss the frequency shift of the most prominent modes, *i.e.*, R1 and R12. In the experimental spectra, we observed the frequency of mode R1 ( $f_{\text{R1}}$ ) increases while mode R12 ( $f_{\text{R12}}$ ) decreases when  $s$  is increased from 90 nm to 345 nm in agreement with the simulated FMR spectra. The frequency shift can be explained by considering the variation of the demagnetizing field with the increase of  $s$  for the resonance areas of modes R1 and R12. The  $X$  and  $Y$  components of the demagnetizing field ( $H_{\text{d}}$ ) for  $H_{\text{app}}$  along the  $X$  and  $Y$  directions at point  $c$  have been

extracted from OOMMF simulations as functions of  $s$  and plotted in Fig. 4. We observed that the  $H_{\text{d}}$  at point  $c$  becomes negative when  $H_{\text{app}}$  is applied along the  $+X$  direction and positive when  $H_{\text{app}}$  is applied along the  $+Y$  direction. From a qualitative standpoint, this behavior can be elucidated by treating the region around point  $c$  as a rectangular magnet outlined by the green dashed line. Point  $c$  experiences a greater demagnetizing field (opposite to the magnetization orientation) when  $H_{\text{app}}$  is along the  $+X$  direction than when  $H_{\text{app}}$  is along the  $+Y$  direction. This discrepancy arises because the  $X$  direction represents the short axis of the rectangular magnet, leading to a negative  $H_{\text{d}}$  at point  $c$  when  $H_{\text{app}}$  is along the  $+X$  direction. It is important to note that the actual value of  $H_{\text{d}}$  is influenced not only by the green magnet but also by the collective field exerted by the five magnets (one green and four yellow magnets). When  $H_{\text{app}}$  is applied along the  $+Y$  direction,  $H_{\text{d}}$  becomes positive, considering the contribution from the four yellow magnets. The absolute values of  $H_{\text{d}}$  exhibit a decreasing trend due to the increasing spacing between magnets. As the spacing ( $s$ ) increases, the fields exerted by these five magnets diminish. Consequently, the nanostructure behaves more akin to a large film with increasing  $s$ , causing  $H_{\text{d-x}}$  and  $H_{\text{d-y}}$  to converge to 0.

As a result, point  $c$  has a larger internal field ( $H_{\text{int}}$ ) for  $H_{\text{app}}$  applied along  $Y$  ( $H_{\text{int}} = H_{\text{app}} + H_{\text{d}}$ ) than  $H_{\text{app}}$  along  $X$  ( $H_{\text{int}} = H_{\text{app}} - H_{\text{d}}$ ). This explains the larger resonance frequency of mode R12 compared to mode R1 for all the  $s$  investigated. We also observed that the absolute value of  $H_{\text{d}}$  decreases with an increase in  $s$  for both  $H_{\text{app}}$  directions. Consequently, for mode R1, the  $H_{\text{int}}$  of its resonance area increases as  $s$  increases, while for mode R12, the  $H_{\text{int}}$  decreases as  $s$  increases. It explains how  $f_{\text{R1}}$  increases while  $f_{\text{R12}}$  decreases with an increase in  $s$ .

We can also understand the change of  $f_{\text{R1}}$  and  $f_{\text{R12}}$  with  $s$  qualitatively. As  $s$  increases, the antidot structure will behave more like a continuous un-patterned film with a resonance frequency ( $f_{\text{cont}} = 11.2$  GHz in our reference film) independent of  $H_{\text{app}}$  directions. So  $f_{\text{R1}}$  and  $f_{\text{R12}}$  approach the  $f_{\text{cont}}$  of the con-



**Fig. 4** (a) Schematic diagram of the rhombic unit cell. Point  $c$  is the center of the rhombic unit cell. (b) The  $X$  and  $Y$  components of the demagnetizing field ( $H_{\text{d}}$ ) for  $H_{\text{app}}$  along the  $X$  and  $Y$  directions respectively, at point  $c$  as a function of  $s$ .



tinuous film when  $s$  is increased. This may, therefore, explain the convergent trend of  $f_{R1}$  and  $f_{R12}$  as  $s$  is increased.

Fig. 5(a) shows the experimental FMR absorption spectra of honeycomb antidot lattices taken at  $H_{\text{app}} = -1400$  Oe along the  $X$  and  $Y$  directions as a function of  $s$ . Unlike rhombic lattices, the FMR spectra for  $H_{\text{app}}$  along  $X$  and  $Y$  directions are similar. The corresponding simulated FMR spectra of honeycomb antidot lattices for  $H_{\text{app}}$  along the  $X$  and  $Y$  directions as a function of  $s$  are shown in Fig. 5(b). There is good agreement between the experimental and simulated results.

For  $s = 90$  nm, three distinct modes H1 (9.1 GHz), H2 (12.1 GHz) and H3 (15.8 GHz) is observed for the spectrum of  $H_{\text{app}}$  along  $X$  direction and three modes H4 (9.9 GHz), H5 (12 GHz) and H6 (16.5 GHz) for  $H_{\text{app}}$  along  $Y$  direction. As  $s$  is increased to 170 nm, we observed that the prominent mode H2 splits and the frequency of prominent mode H5 ( $f_{H5}$ ) decreases to 11.8 GHz. As  $s$  is further increased to 345 nm, mode H2 ( $f_{H2}$ ) frequency decreases to 11.6 GHz, and mode H5 ( $f_{H5}$ ) decreases to 11.5 GHz. We have observed an overall convergence of modes H (1–3) and H(4–6) as  $s$  increases.

We have plotted the profiles for the observed modes H (1–6) for different  $s$  in Fig. 6. For  $s = 90$  nm, we found that mode H1

extends as a continuous resonant stripe along  $Y$  while mode H4 extends as another continuous stripe along  $X$  enclosed by the holes. Note that there is only a single stripe for mode H1 within one honeycomb unit cell, while there are two stripes for mode H4. Modes H2 and H5 are localized at the central region of the honeycomb unit cell. Mode H3 is enclosed between two nearest-neighbor holes in the rows of holes along  $\theta = -\frac{\pi}{6}$  directions, and H6 is enclosed between two nearest-neighbor holes in the horizontal rows of holes. For  $s = 170$  nm, modes H1, H4, H5 and H6 show a similar profile to that for  $s = 90$  nm. Mode H2 becomes triplet modes and is localized in different areas within the hexagonal unit cell. Mode H3 is enclosed between two nearest-neighbor holes in the rows of holes along  $\theta = \frac{\pi}{6}$  directions. For  $s = 345$  nm, mode H1 extends as a more uniform resonant stripe along  $Y$  compared with the cases of  $s = 90$  and 170 nm, which show a more concentrated spin precession amplitude between two horizontal nearest-neighbor holes. Mode H3 becomes too weak to be identified, while Mode H4 displays a symmetry node in the middle region between rows of holes with a peak amplitude near the holes' edges. This mode profile evolution of H4 is similar to that of mode R7 in the rhombic antidot lattice.

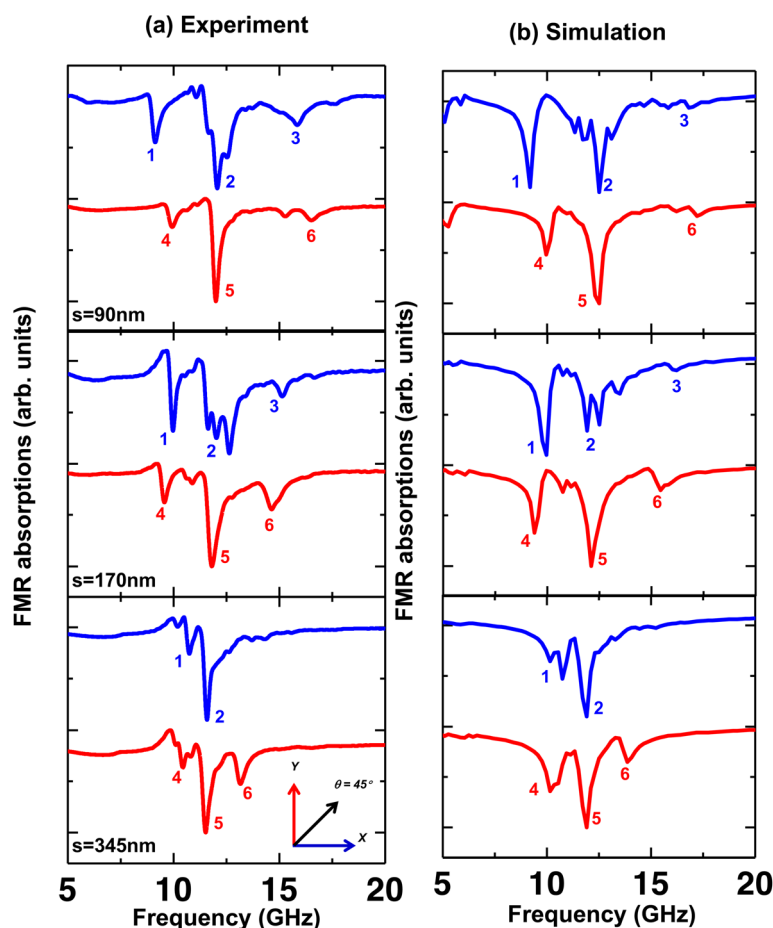
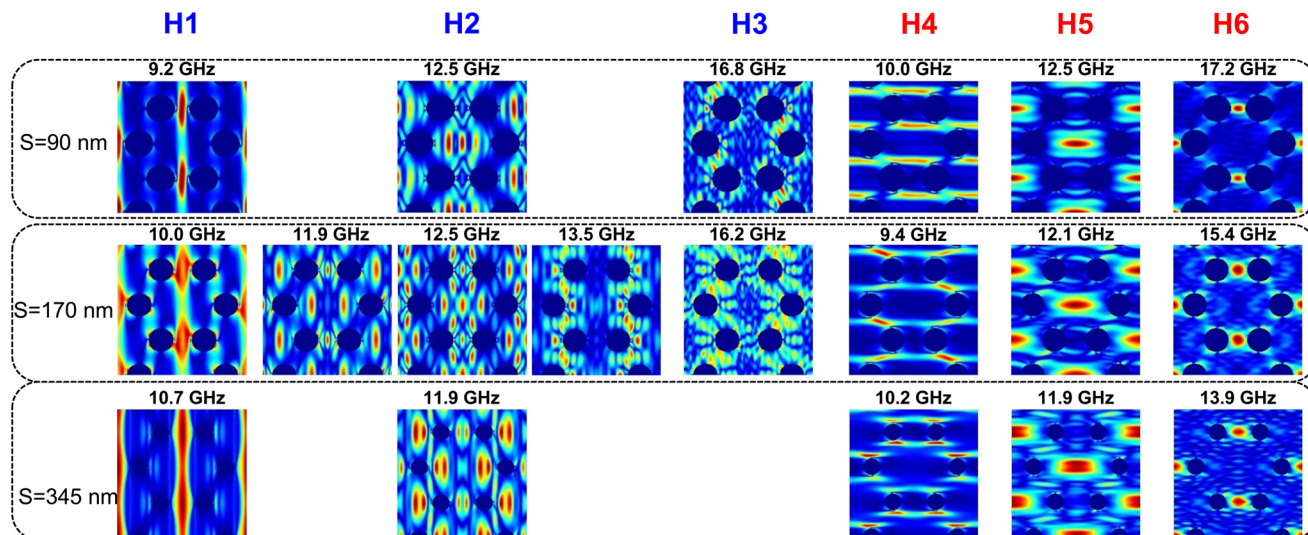


Fig. 5 (a) Experimental and (b) Simulated FMR spectra of 25 nm thick permalloy honeycomb antidot lattices as a function of  $s$  taken at  $H_{\text{app}} = -1400$  Oe along the  $X$  and  $Y$  directions.







**Fig. 6** Spatial profiles of modes in the simulated FMR spectra taken at  $H_{\text{app}} = -1400$  Oe along  $X$  and  $Y$  directions of 25 nm thick permalloy honeycomb antidot lattices as a function of  $s$ .

It is worth noting that the resonance frequency variations with  $H_{\text{app}}$  direction and  $s$  are less pronounced in the honeycomb antidot lattice than in the rhombic antidot lattice discussed earlier. For example, as  $s$  is increased from 90 nm to 345 nm, the frequency shifts of prominent modes H2 and H5 are small ( $\sim 0.5$  GHz) compared with what was observed for rhombic antidot lattice where a distinct frequency shift of 1.7 GHz for mode R1 and 2.7 GHz for mode R12 with  $s$  increasing from 90 nm to 345 nm. The marked difference between rhombic and honeycomb antidot lattices is attributed to an additional hole at the central region of the hexagonal unit cell in the rhombic lattice. The presence of an additional hole induces a larger variation in demagnetisation field as a function of  $s$ . Consequently, it produces a larger resonance frequency modification with  $s$  and different  $H_{\text{app}}$  directions.

## Conclusions

In summary, we have systematically investigated the effects of inter-hole spacing and lattice (rhombic and honeycomb) arrangements on the dynamic responses of  $\text{Ni}_{80}\text{Fe}_{20}$  antidot structures. We also showed that the dynamic behaviors of antidot structures are very sensitive to the  $s$  and  $H_{\text{app}}$  directions. By changing the  $s$  and  $H_{\text{app}}$  direction, a marked variation in mode frequency, mode intensity and number of modes is observed. Our experimental results are in good agreement with micromagnetic simulations. These results may find useful applications in the design of tunable microwave filters and magnonic devices.

## Author contributions

A. O. A. conceived the project. CT fabricated the samples and carried out the experiments. A. O. A. supervised the overall

project. All authors discussed the results and co-wrote the manuscript.

## Conflicts of interest

There are no conflicts to declare.

## Acknowledgements

A.O.A would like to acknowledge the funding from the Wolfson Foundation and Royal Society. The authors thank Dr Navab Singh for the DUV templates.

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