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Supplementary Materials for

Voltage-driven, local, and efficient excitation of nitrogen-vacancy centers in diamond

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Section S1. Comparison of power efficiency between NV-FMR and NV-ADFMR couplings

Previous work by the co-authors measured coupling between NV centers in crystalline nanodiamonds and a proximal, resonating Yittrium Iron Garnet (YIG) film (*5*). The YIG film was driven into resonance through applied microwave excitation via a lithographically defined stripline. A plot of the measured NV PL change as a function of frequency can be found in fig. S1. The first peak (at approximately 600 MHz) corresponds to the off-resonant coupling between the NV centers and the resonating ferromagnet. The signals at 1.4 and 2.8 GHz are direct drive peaks showing resonant coupling to the NV centers directly due to the stripline excitation. The largest response to FMR (of approximately 0.75%) shown is for a power level of +24 dBm (approximately 250 mW) at the NV center location. Microwave power was decreased in steps of 3 dB from +24 dBm to +3 dBm, corresponding to the curves with lower amplitude.

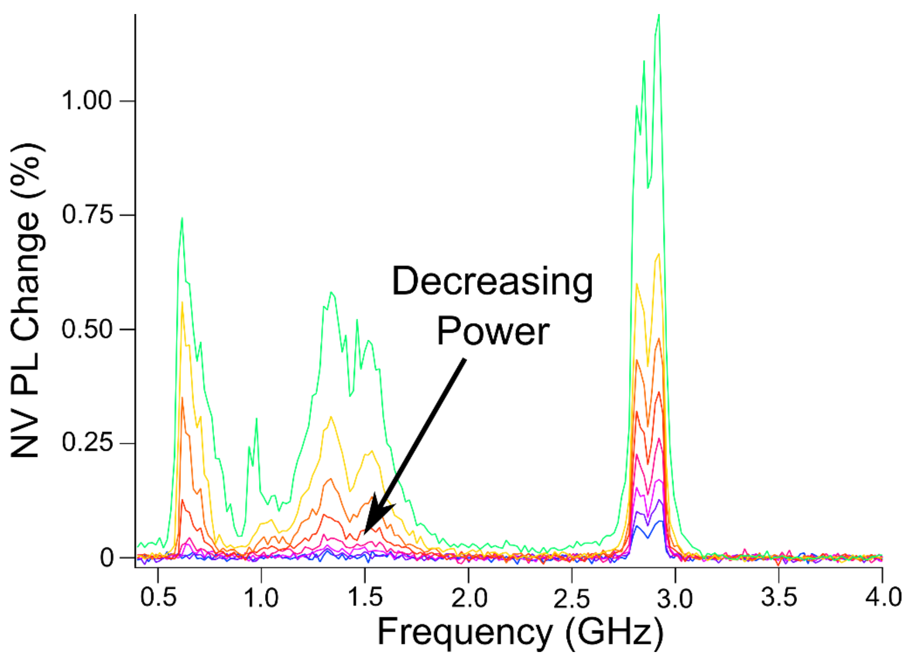

Fig. S1. NV PL change as a function of RF power at the NV center location. The three peaks in the frequency spectrum represent the NV-FMR coupling, excited state coupling, and ground state coupling, respectively. Eight spectra are plotted – covering the range between +24 dBm and +3 dBm in 3 dB steps. At +24 dBm, the peak NV PL change due to NV-FMR coupling can be observed to be approximately 0.75%. Modified from Ref. (*5*) with permission from the authors.

In the present work, a comparable change in NV PL can be observed with an RF power several orders of magnitude lower than that shown in fig. S1. For example, at an excitation frequency of 1429 MHz, a similar PL change is observed despite the incident acoustic power on the magnetic element being at most 0.19 mW. Comparing these two figures gives an efficiency enhancement for the magnetoelastic drive of approximately 1300 times. Performing this same comparison at 287 and 861 MHz results in calculated efficiency enhancements of approximately 30 and 100 times, respectively.

While this serves as an effective comparison in terms of order of magnitude, a number of differences keep this comparison approximate. Firstly, the two measurements were performed using different measurement setups and on different nanodiamond clusters (with different NV-ferromagnet spacings). As can be seen in Section III, such differences can account for a 5x change in observed NV PL change for the same sample. In addition, the YIG films used in the previous work have substantially lower damping than the nickel and cobalt films measured in this study. Due to the broadening of the FMR peak caused by this damping, the expected peak amplitude of the signal should be lower in Ni and Co films. As a result, we believe that this excitation efficiency improvement is in fact a lower bound for what may be possible with the NV-ADFMR system.

Section S2. Calculation of power at the magnetic element

By using the time-gating technique discussed in the materials and methods section, it is possible to very precisely calculate the transmitted acoustic power in ADFMR devices. Performing these measurements at high applied magnetic field (where power absorption due to ADFMR can be taken to be zero) allows us to characterize the insertion loss of the devices that is due to the transducer geometry and construction. Since propagation loss in the substrate is very small compared to the measured insertion loss (*23*), it is assumed that all power is lost at the transducer elements. Thus, the acoustic power incident on the magnetic film is simply the input power minus half the total device insertion loss (in dB).

Total insertion losses for the ADFMR devices operating at 287, 861, and 1429 MHz were measured to be 16.9, 22.0, and 44.4 dB, respectively. Assuming a completely lossless RF signal path, a +15 dBm signal is seen at the device input port. This corresponds to power levels at the magnetic element of 4.52 mW for the 287 MHz excitation, 2.51 mW for 861 MHz, and 0.19 mW for 1429 MHz. These values set an upper limit for the maximum possible power delivered to the magnetic element.

Section S3. Comparison of measurement setups

Data presented in Fig. 3(b) of the main text was collected on a different measurement setup than data in Figs. 3(a) and 4. The configurations of both setups were comparable, and measurements in both setups were performed on the same sample. The second setup was used for data collection for Fig. 3(b) due to a better understanding of losses in the system, as well as higher precision movement and scanning capabilities. While there are differences in optical and RF losses in the two systems leading to a difference in the magnitude of the measured NV PL change, fig. S2 below shows that there is good qualitative agreement between data collected from the two sets of measurement equipment.

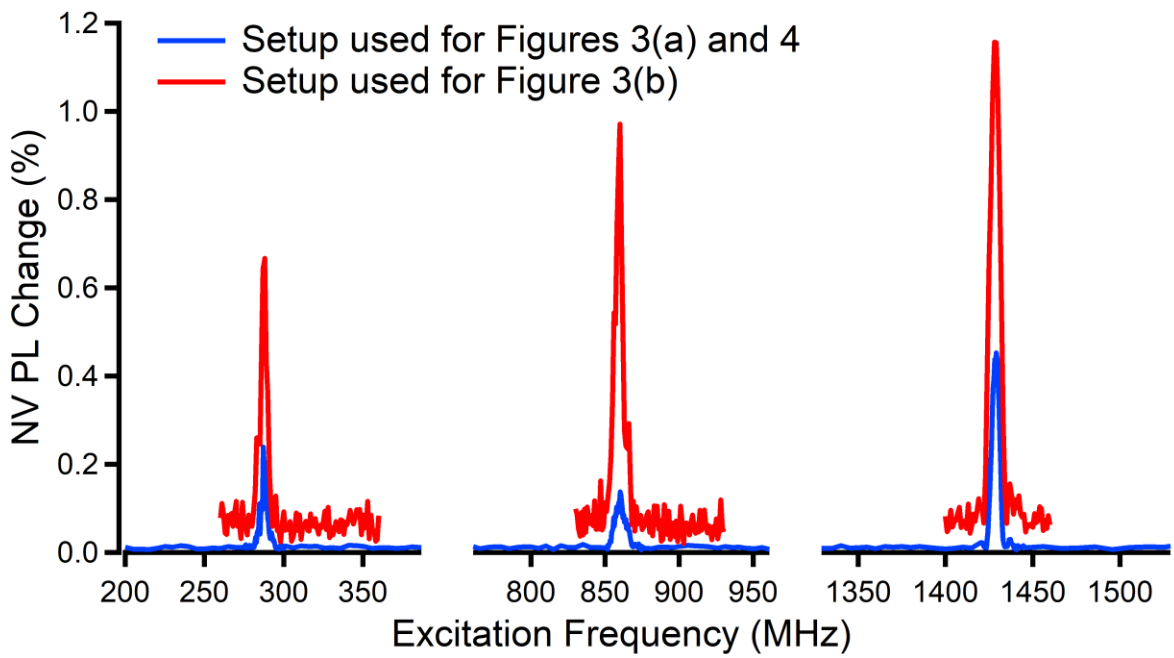

Fig. S2. NV PL change as a function of frequency for the two measurement setups used in this work. The blue spectra correspond to the setup used to collect data for Figs. 3(a) and 4 in the main text, and the red spectra correspond to the setup used to collect data for Fig. 3(b). A close qualitative agreement can be seen between the two sets of data.