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A compact radiofrequency spectrum analyzer based on nitrogen-vacancy centers in diamond

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ABSTRACT

We have realized a compact radiofrequency spectrum analyzer based on nitrogen-vacancy (NV) color centers in diamond. The RF spectral components are spatially encoded by means of a Zeeman shift of the NV resonances induced by a magnetic field gradient. The fluorescence of the NV centers is imaged on a CMOS detector array using a gradient index lens. The spectral components of the signal are revealed by the appearance of dark lines in the image. We observed frequencies up to 10 GHz, with a resolution of a few MHz and a RF sensitivity of the order of 100 μ W.

Keywords: diamond, color center, nitrogen-vacancy, optically detected magnetic resonance, wide-field imaging, radiofrequency field, spectrum analyzer, microwave field.

1. INTRODUCTION

The nitrogen-vacancy center (NV) is a spin-1 diamond color center constituted of a nitrogen atom and a carbon vacancy in two adjacent positions of the tetrahedral diamond lattice. It presents remarkable room-temperature spin-dependent optical properties, which make it a promising candidate for quantum sensing and quantum technologies applications. Its electron spin can be optically polarized and read out as well as coherently manipulated by means of a resonant MW field over a coherence time (T_2) of a few ms, which allows the optical detection of its magnetic resonance (ODMR). For this reason, in the last decades, several NV-based applications have been developed such as magnetometers, electrometers, thermometers or high pressure sensors [1].

Real-time detection and broadband spectral analysis of radio frequency (RF) signals have become essential for telecommunications today. The main solution is the Fast Fourier Transform (FFT) electronic spectrum analyzer. A high frequency analog-to-digital converter (ADC) digitizes the RF signal that is then processed by Fourier analysis. However, the sampling rate and power consumption of the ADC limit the real-time bandwidth to a few hundred MHz. An alternative technique is to use the spin quantum properties of an ensemble of NV centers to optically detect RF signals at room temperature, without analog-to-digital conversion nor optical processing module.

2. PRINCIPLE

The use of NV centers for the spectral analysis of microwave signals relies on the spatial encoding of their RF resonance frequency by means of a magnetic field gradient (Figure 1). Two resonances can be observed corresponding to the transition from the spin 0 level to the spin -1 and spin +1 levels respectively. Their frequencies are identical and equal to $D=2.87$ GHz at zero magnetic field and they vary linearly when increasing the magnetic field. At Ground State level Anti-crossing (GSLAC), the energy of the spin -1 level is equal to the one of the spin 0 level and the resonance frequency is zero. The instantaneous spectral content of an RF signal of interest is transposed onto the local photoluminescence level of an ensemble of NV centers contained in a diamond crystal and optically pumped. The complete frequency spectrum of a complex signal can thus be reconstructed from the image of the spatial distribution of the photoluminescence signal emitted by the NV centers with an interception probability close to 100% over a wide instantaneous band.

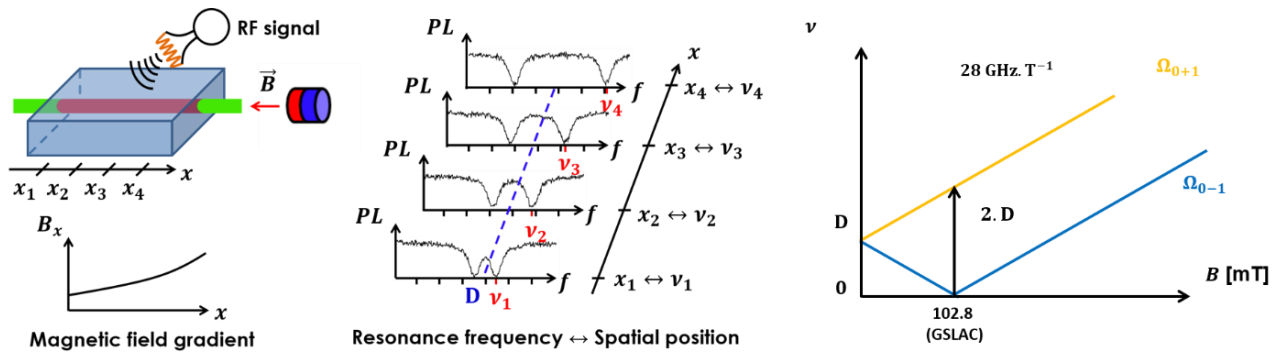


Figure 1 Principle of the NV center based spectrum analyzer describing the spatial encoding of the resonance frequency induced by the magnetic field gradient.

3. EXPERIMENT

The proof of principle of this technique had been first established by demonstrating the coverage of a band of a few hundred MHz around 2 GHz and where the main technical limitation came from the constraint related to the alignment of the magnetic field with respect to the NV centers [2]. In a subsequent demonstration, we have extended the frequency range up to 25 GHz [3]. Here, we describe a compact device comprising a diamond crystal with a specific cut, a ring magnet to create the magnetic field gradient aligned with the pump laser at 532 nm and a compact antenna to bring the RF signal in the vicinity of the diamond crystal (Figure 2). The entrance face of the diamond crystal is [111] cut, which allows aligning both the magnetic field gradient and the laser beam with the direction of one of the four NV center families. This induces a linear Zeeman shift of the resonance and keeps a good contrast of the OMDR signal even when a strong field is applied. The fluorescence of the NV centers is imaged on a CMOS detector array using a gradient index lens. This makes possible a much more compact imaging device as compared to previous implementations [3], while preserving a good image quality. The laser beam is focused through the ring magnet and aligned with the magnetic field gradient.

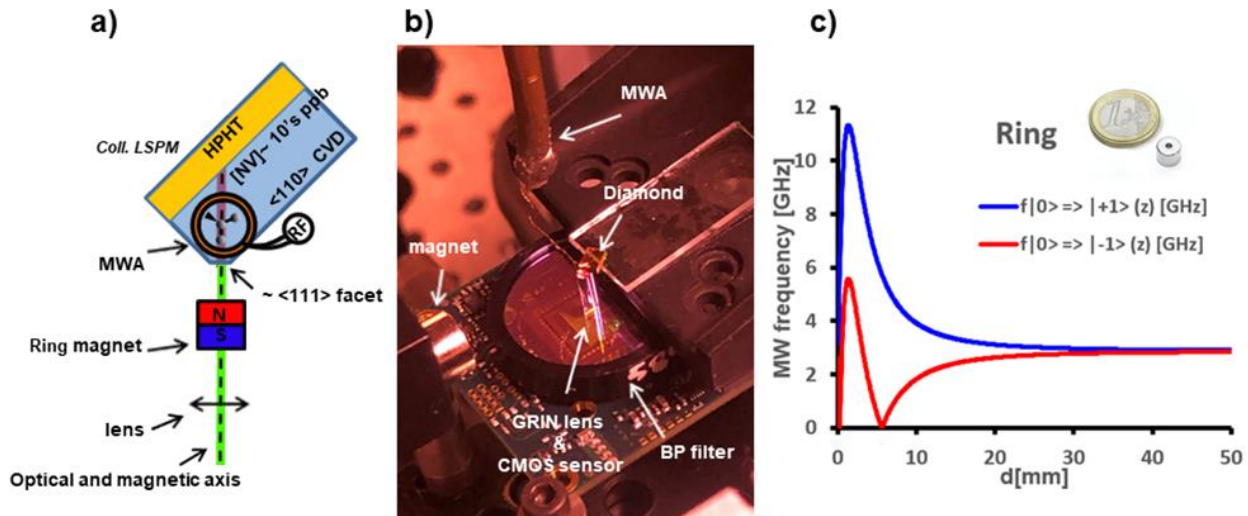


Figure 2: scheme and picture of the compact NV spectrum analyzer as well as the frequency range achieved with the cylindrical magnet.

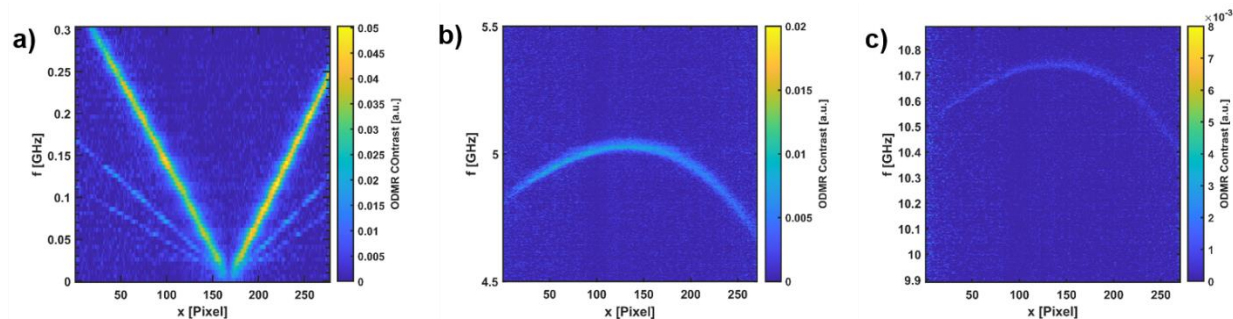


Figure 3: Resonance frequency near GLSLAC showing a minimum frequency of 10 MHz (a). The highest value of the spin 0 to spin -1 transition is slightly above 5 GHz (b). The highest value of the spin 0 to spin +1 transition is 10.7 GHz, which gives the upper value of the frequency range (c).

4. RESULTS

The spectral components of the signal are reflected by the appearance of resonance lines in the luminescence image (bright lines on figure 3). The lower frequency is in the order of 10 MHz and is obtained on the spin 0 to spin -1 transition around GSLAC (figure 3-a). The bright lines show the linear dependence of the resonance frequency with the magnetic field. The other lines are due to harmonics of the fundamental RF signal and can be used to evaluate the dynamics of the detection [3]. In this range, the RF sensitivity is of the order of 100 μ W and the frequency resolution of a few MHz. According to figure 2-c, the maximum value achievable on this resonance with this ring magnet is slightly above 5 GHz, which is shown on figure 3-b. The spin 0 to spin +1 transition is well suited to address the 5 GHz to 10 GHz range, which gives the upper frequency range of the spectrum analyzer (figure 3-c).

5. CONCLUSION

This is a first step towards a compact device for sensitive and broadband spectral detection and analysis of RF signals. Several directions can be investigated to improve the performances. The signal to noise ratio and the sensitivity can be improved using a diamond crystal with increased NV concentration up to the ppm level or a crystal with NV preferential orientation to suppress the background signal of the three other NV families. A more compact device could be made possible with the use of a diode laser diode or assembling all active elements directly on the diamond crystal.

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