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Strongly driven electron spins using a K_u band stripline electron paramagnetic resonance resonator

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ABSTRACT

This article details our work to obtain strong excitation for electron paramagnetic resonance (EPR) experiments by improving the resonator's efficiency. The advantages and application of strong excitation are discussed. Two 17 GHz transmission-type, stripline resonators were designed, simulated and fabricated. Scattering parameter measurements were carried out and quality factor were measured to be around 160 and 85. Simulation results of the microwave's magnetic field distribution are also presented. To determine the excitation field at the sample, nutation experiments were carried out and power dependence were measured using two organic samples at room temperature. The highest recorded Rabi frequency was rated at 210 MHz with an input power of about 1 W, which corresponds to a $\pi/2$ pulse of about 1.2 ns.

1. Introduction

In a typical electron paramagnetic resonance (EPR) system, electron spins are excited by a magnetic field, $\mathbf{B}_1$ induced from a microwave pulse in a static magnetic field, $\mathbf{B}_0$. For most situations, all of the intended operations must be completed before the spin relaxes to the environment and irreversibly losses its information. This limits the number of operations that can be performed on the spins. Pulsed EPR experiments using complex or long pulse sequences will find difficulties dealing with samples of short coherence time (i.e. samples with broad linewidth). One approach to prolong coherence time is to eliminate sources of decoherence within the sample by isolating spins in vacuum-like environments [1–3]. Another approach is to cool samples to cryogenic temperatures [4]. A useful improvement is to increase the excitation capabilities of the EPR system, which depends on the pulse power as well as the resonator's microwave power-to-field conversion factor, Λ (sometimes called as microwave efficiency parameter) [5]:

$$\Lambda = \frac{B_1^r}{\sqrt{P}} \tag{1}$$

where P is the pulse power and $B_1 = 2B_1^r \cos(\omega t)$ which takes into account the magnitude of the resonant circularly polarized component in a linearly polarized microwave field. One may choose to apply high power to a less efficient resonator but this approach is often restricted by technical complexity and cost to apply high power especially at high frequencies. For certain cryogenic experiments, this approach contributes to unwanted heating problems. Alternatively, an efficient resonator reduces the required power to achieve the same degree of rotation. Furthermore, $\mathbf{B}_1$ is reciprocal to the generated electromotive force during detection, thus an efficient resonator displays both high sensitivity and the ability to strongly drive electron spins [6].

To improve a resonator's efficiency, one may increase its Q factor or improve its filling factor. For a pulsed EPR system, increasing the Q factor is unfavorable since it prolongs dead-time after excitation [7]. In terms of the resonator's bandwidth, a high Q resonator prohibits the use of nano-second microwave pulses. As a result, most researchers opt to scale down and improve the filling factor instead. For samples of large volume, conventional large resonators are able to reach high filling factors. For smaller sample sizes, scaling down the resonator works better to increase the filling factor and to concentrate the induced current [8–10]. For a cavity resona-

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tor, its dimension determines the resonant frequency [11] hence it is not possible for further size reduction. Loop-gap resonators are smaller than cavity resonators [12] but are harder to fabricate especially in small sizes. Microcoils are good at concentrating magnetic fields around the sample but require delicate techniques to wind a wire of tens of micrometers [13,14]. It is possible to scale down a dielectric resonator since its resonant frequency is a function of its dimension and permittivity. Unfortunately, size reduction is ultimately limited by availability of high permittivity materials.

For our research, we decided to work on a stripline resonator due to its ease of design implementation. Micro-stripline provides equal flexibility but generally have higher radiation losses. These planar structures have small resonator volume, which inherently have high filling factor. Realizing this, various groups have been investigating planar structures [9,10,15–18], planar microcoils [19,20] and some with structures as small as 20 μm [8,21].

In this paper, we present our work on stripline resonators tested with our homemade spectrometer operating at about 17 GHz. With this setup, we demonstrated a Rabi frequency of about 210 MHz ($\pi/2$ pulse = 1.2 ns) with an input power of about 1 W at room temperature. Here, we describe the design, simulation, fabrication, and testing of two stripline resonators.

2. Design and simulation

The workflow started with design and simulation using finite-difference time-domain (FDTD) solver (CST Microwave Studio). The stripline layout is composed of a flat conductor sandwiched between insulators and parallel ground planes (see Fig. 1). In the near future, these resonators would be used in our cryogenic systems and to avoid problems arising from multiple reflections due to numerous connections within the system, we decided to use transmission-type resonators. This reduces the resonator's efficiency by almost half as compared to a reflection-type resonator. The design can be easily change into a reflection-type resonator by removing the redundant feed line.

2.1. Basic design

We begin by explaining the properties of a basic resonant strip, followed by two of our proposed designs: butterfly design and U-shape design. The standard design in Fig. 2a was first proposed by Johansson et al. [22]. As a half-wavelength resonator, the current and voltage density are distributed laterally with higher current density in the middle section and higher voltage density at both ends of the resonant strip. This couples the resonant strip to the feed lines capacitively. The resonant frequency was estimated using:

$$l + 2\Delta l = \frac{c}{2f_0\sqrt{\varepsilon_{\text{eff}}}} \quad (2)$$

where l is the length of the resonant strip, $2\Delta l$ accounts for the fringing fields at both ends, f_0 is the resonant frequency and ε_{eff} is the effective dielectric constant of the substrate [11]. The feed lines width was calculated to achieve an impedance of 50 Ohms at 17 GHz and the width of the resonant strip was made to match.

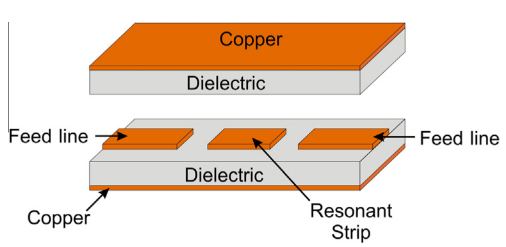

Fig. 1. The standard stripline resonator as first proposed by Johansson et al. [22].

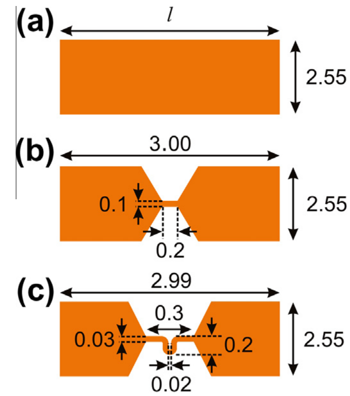

Fig. 2. The designs and dimensions of several stripline resonators: (a) basic resonator, (b) butterfly resonator and (c) the U-shape resonator. All dimensions are in millimeters.

2.2. Butterfly design

Starting from the basic design in Fig. 2a, the resonator size was reduced by narrowing the middle section with a taper as shown in Fig. 2b. For convenience purposes, this design is called butterfly resonator. Samples could be deposited directly on the copper surface in the middle of the narrow section. Since current density is maximum in the middle of the resonant strip, the narrow section functions to further concentrate magnetic flux around the sample whereas tapering minimizes reflection of the input pulse [23].

Modifications to the basic design changes the resonant frequency, which is easily reverted by adjusting l. Initially, coupling adjustment was done during simulation by altering the distance between the feed lines and resonant strip. Once fabricated, this method is somewhat permanent and lacks flexibility. To overcome this problem, the feed lines and resonant strip were separated between the two layers of the stripline resonator. By moving one layer away from the other, the coupling between the feed lines and resonant strip can be adjusted as shown in Fig. 3. Notes on practical implementation are provided in the following section.

FDTD analysis estimated a peak B_1^r value of about 1.8 mT (50 MHz) with an input pulse power of 1 W. The narrow section produces high $\mathbf{B}_1$ but also high $\mathbf{B}_1$ inhomogeneity (refer to Fig. 4). Design optimization and detailed explanation for a nuclear magnetic resonance (NMR) resonator are provided in Ref. [9] and will not be repeated here. Upon closer inspection, within the narrow section, current density concentrates at the edges of the strip and can be approximated as two parallel current-carrying wires (refer inset image in Fig. 4). As a result, the $\mathbf{B}_1$ component perpendicular to $\mathbf{B}_0$ peaks inside the dielectric layer, making it difficult to place the sample.

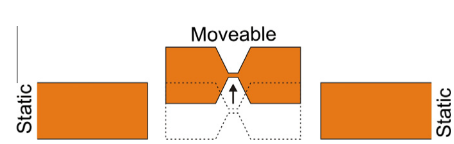

Fig. 3. A moveable resonant strip was employed for coupling adjustment. The dotted line indicates the original position of the resonant strip and the arrow shows the direction of displacement. The actual displacement ranges from 0 to 3 mm.