Journal of Magnetic Resonance 230 (2013) 84–87

Contents lists available at SciVerse ScienceDirect

Journal of Magnetic Resonance

journal homepage: www.elsevier.com/locate/jmr

Superconducting microstrip resonator for pulsed ESR of thin films

O.W.B. Benningshof [a,b,*], H.R. Mohebbi [a,c], I.A.J. Taminiau [a], G.X. Miao [a,c], D.G. Cory [a,d,e]

[a] *Institute for Quantum Computing, Waterloo, ON, Canada*
[b] *Department of Physics, University of Waterloo, Waterloo, ON, Canada*
[c] *Department of Electrical and Computer Engineering, University of Waterloo, Waterloo, ON, Canada*
[d] *Perimeter Institute for Theoretical Physics, Waterloo, ON, Canada*
[e] *Department of Chemistry, University of Waterloo, Waterloo, ON, Canada*

A R T I C L E I N F O

Article history:
Received 17 August 2012
Revised 24 January 2013
Available online 5 February 2013

Keywords:
EPR
Superconducting resonator
Cavity quantum electrodynamics
Strong coupling
Nutation spectroscopy

A B S T R A C T

This article describes a superconducting microstrip resonator operating at 9.5 GHz (X-band) that is specially designed for pulsed ESR on thin films. A novel configuration consisting of an array of half-wave length microstrip transmission lines generates a uniform magnetic field over a 2-D region of $100 \times 1000\ \mu m^2$ with field homogeneity better than 5×10^{-2}. Using the device, we demonstrate strong coupling of the resonator to an electron spin ensemble and pulsed ESR on Si:P.

1. Introduction

Electron spin resonance (ESR) is a powerful technique in chemistry and materials science and has increasingly been used to generate control sequences for quantum information processing [1]. Improved sensitivity for thin film samples would benefit all of these. To observe small ensembles with high signal-to-noise ratio (SNR) one needs to realize a high *Q* resonator, have high spin polarization, and tailor the microwave magnetic field of the resonator to the geometry of the sample. Here we introduce a new superconducting resonator that is optimized for the study of 2-D samples.

High resolution ESR benefits from having both a homogeneous external field B_0 and a uniform microwave field B_1. The latter improves sensitivity and simplifies the spin dynamics. Microwave cavities can fulfill these requirements, however their filling factor is small for thin film samples. The development of superconducting planar coils [2,3] and coplanar waveguide (CPW) resonators [4–11] have increased the filling factor significantly, but their B_1 fields are not uniform over a broad 2-D region necessary to study thin films.

Here we report a superconducting microstrip resonator operating at X-band frequencies, based on a novel design of half-wave microstrip transmission lines. An array of microstrip lines provide a high *Q* resonance at the desired frequency, which generates an in-plane uniform magnetic field suitable for pulsed ESR experiments on thin films. The performance, high sensitivity and small mode volume are verified by demonstrating strong coupling of the resonator to an ensemble of electron spins in perchlorotriphenylmethyl (PTM) and by performing pulsed ESR of a phosphorus doped silicon sample Si:P.

2. The microstrip resonator

Schematic of the microstrip resonator is shown in Fig. 1. A custom designed, in-phase 1–4 power splitter couples the microwave $\lambda/2$ microstrip line resonator. The coupling strength is controlled by coupling the splitters capacitively to the strip lines. The power splitter was designed to maintain impedance matching for maximum power transfer. The length of the $\lambda/2$-resonator was chosen to have a fundamental resonance frequency ω_r (on a sapphire substrate) of 9.5 GHz. The design ensures that all lines resonate in phase. By optimizing the height of the sample above the resonator, the sample experiences a magnetic field with high in-plane uniformity (see Fig. 2). Simulations (Ansoft HFSS [12]) show a magnetic field homogeneity of $\sim 10^{-2}$ (for a range of 100 μm) at 100 μm above the resonator. The homogeneity in the *z*-direction is mainly due to the boundary conditions of the $\lambda/2$-resonators, forming a half sine wave between the ends of the strip line. We restrict the sample to the central 2-D area of $100 \times 1000\ \mu m^2$, which has (100 μm above the resonator) a homogeneity of approximately 5×10^{-2}. We will refer to this area as the 'uniform region'. In general the width (*y*-direction) of this uniform region is

* Corresponding author at: Institute for Quantum Computing, Waterloo, ON, Canada. Fax: +1 519 888 7610.

E-mail address: obenning@uwaterloo.ca (O.W.B. Benningshof).

1090-7807/$ - see front matter © 2013 Elsevier Inc. All rights reserved.
http://dx.doi.org/10.1016/j.jmr.2013.01.010

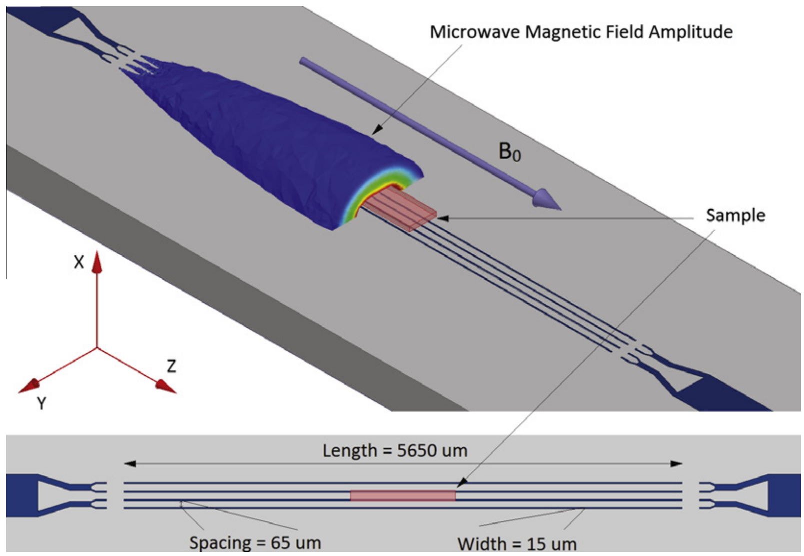

Fig. 1. The device consists of four parallel $\lambda/2$ microstrip line resonators, which are separated by 65 µm. One $\lambda/2$-resonator is 5650 µm long, 15 µm wide and 200 nm thick. It is structurized on a 430 µm thick sapphire wafer, which has a Nb ground plane on the underside. The sample is placed on top and in the center of the resonator. It is excited by a microwave magnetic field B_1. Because of symmetry only one half of the amplitude of the microwave magnetic field is shown, so that the resonator structure and the sample position are visible. When the thin film is placed in the uniform region (square in topview figure) the B_1 field is mainly determined by its y-component. The static magnetic field is applied along the z-axis, which enables pulsed ESR in a thin film. We have fabricated resonators with up to 16 parallel striplines.

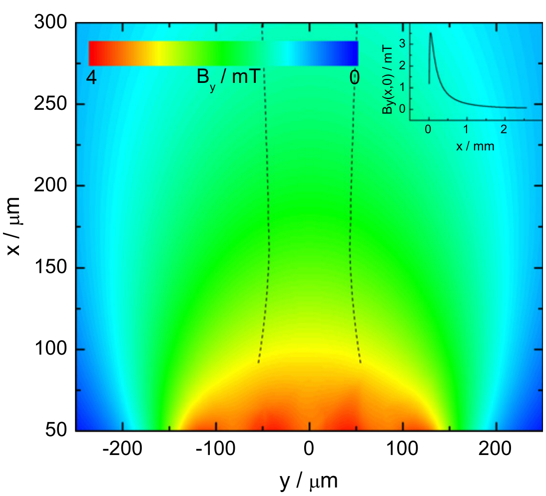

Fig. 2. The simulated profile of B_y above the middle of the microstrip resonator when excited by a 50 Ω source providing 1 W. Spatial variation in the magnetic field is large near the surface of the substrate but reduces continuously for higher levels such that good uniform magnetic fields are achieved 100 µm above the resonator. Between the dashed-lines (width of roughly 100 µm) the field homogeneity $|B_y(x,y) - B_y(x,0)|/|B_y(x,0)|$ is less than 5×10^{-2}. In the sub-figure (top right corner) is plotted how $B_y(x,0)$ varies with height above the center of the resonator. Between 60 µm and 700 µm the magnetic field strength is in very good agreement with an exponential decay with a characteristic length of roughly 210 µm.

determined by the number of parallel $\lambda/2$-resonators. This width is roughly 100, 400 and 800 µm for 4, 8 and 16 parallel $\lambda/2$-resonators, respectively. The magnetic field strength in the volume above the resonator (x-direction) is in very good agreement with an exponential decay between 60 µm and 700 µm. After 700 µm the magnetic field strength drops typically as $x^{-3/2}$, see Fig. 2.

Our devices were fabricated by sputtering a 200 nm thick layer of Niobium (Nb) on both sides of a C-orientated sapphire substrate with a thickness of 430 µm, patterned by photolithography and followed by reactive ion etching using sulfur hexafluoride (SF_6). The resulting device measured 0.3×1.3 cm^2 and was mounted in the middle of a top-plated microstrip line carrier printed circuit board (PCB) by silver paint to ensure thermal and electrical anchoring. The device and PCB are connected by aluminum wire bonds and all are enclosed in a copper package with two SMA connectors.

Superconducting resonators can obtain a Q of $\sim 10^5$ for 10 GHz [13,14] at the lowest temperatures. Here the Q is determined by the external losses ($\propto 1/Q_E$) and the intrinsic losses ($\propto 1/Q_I$), hence $1/Q = 1/Q_E + 1/Q_I$. As the intrinsic losses are strongly temperature dependent the Q increases for lower temperatures. The Q of the resonator used in the experiments (all performed at 4.2 K) described below is 1500.

For optimal power transfer the resonator has to be critically coupled to the transmission lines, controlled by adjusting the size of the gap between the strips and the fingers of the power splitter to match the external losses Q_E to the intrinsic losses Q_I. The observed power transfer during our performed experiments was approximately 10%, yielding a gap size of 150 µm for optimal power transfer at LHe temperatures. Because the Q_I is temperature dependent, the gap should be adjusted for a specific temperature in order to achieve critical coupling. In studies to explore the Q_I temperature behavior we used large gaps (150 µm) and observed Q's as high as 29,000 at 250 mK in the absence of a static external field.

The bulk critical field of Nb ($H_{c_2}(0) \approx 500$ mT and $H_{c_2}(4.2) \approx 300$ mT [15]) is close to the $B_0(\sim 350$ mT) used for the ESR experiments. However, nanostructured Nb [16] increases the critical H_{c_2} significantly, which further increases as the substrate is mounted parallel to the applied magnetic field B_0 [17]. Having a lower reduced-field ($H/H_{c_2}(0) \approx 0.1$) will only moderately change the properties of the resonator (Q and ω_r) with respect to zero field.

3. Strong coupling effects

In the past few years several groups have reported strong coupling effects with an ensemble of microscopic emitters to a superconducting resonator. Examples, all coupled to a CPW resonator, include transmon-type superconducting qubits [5,6], electron-spins in solids [7], and spins in rare earth ions [8] or NV centers [9–11]. Here we demonstrate magnetic strong coupling of the microstrip resonator with an ensemble of electron spins. The