Micrometer-Scale Coplanar Waveguides for Nanoscale Magnetic Resonance Imaging

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Abstract:

We report on the design, fabrication, and characterization of broadband micrometer-scale coplanar waveguides capable of delivering millitesla strength magnetic fields on a 200 milliwatt power budget with minimal sample heating. These waveguides, operating from DC up to 40 GHz, have been integrated into a cryogenic scanning probe microscope to enable the detection of electron spin resonance and nuclear magnetic resonance in a single force detected magnetic resonance experiment for the first time. Additionally, the ability to irradiate both nuclear and electron spins with a single device allowed for the first mechanical detection of hyperpolarized proton magnetization achieved via cross-effect dynamic nuclear polarization [1]. These enabling advances are the first steps toward achieving three-dimensional, nano-scale magnetic resonance imaging (nano-MRI) using magnetic resonance force microscopy.

Figure 1: Schematic of a magnetic resonance force microscope experiment showing the magnet-tipped cantilever and coplanar waveguide necessary to modulate sample spins (adapted from Ref. 3).

Summary of Research:

Having a universal platform for imaging individual biomolecules or biomolecular complexes with isotopic specificity and nanometer or sub-nanometer resolution would be an enabling advance for a variety of scientific disciplines. By detecting magnetic resonance as a force on an attonewton-sensitivity microcantilever (Figure 1), magnetic resonance force microscopy (MRFM) offers the sensitivity and depth-of-view required for three-dimensional, nano-MRI. While recent advances in MRFM have demonstrated the ability to perform 3D imaging of a single virus particle with < 10 nanometer resolution [2] and the sensitivity required to detect a few hundred proton magnetic moments with a record-high gradient magnet tipped cantilever [3], these experiments required hours or days of signal averaging as a result of detecting statistical polarization or random spin fluctuations commonly referred to as ‘spin-noise’.

To achieve greater imaging resolution, while decreasing signal averaging time, our approach was two-fold: (1) increase nuclear spin polarization to generate a well-defined polarized spin signal and (2) develop a universal sample platform in which biological samples can be deposited for single electron spin imaging. The enabling advance for both experiments was a broadband coplanar waveguide (CPW) to deliver radiofrequency waves for nuclear magnetic resonance (NMR), microwave frequency irradiation for electron spin resonance (ESR) and combining these techniques to transfer polarization from nuclear spins to electron spins via dynamic nuclear polarization (DNP). The challenge in the development of these CPWs was to achieve a high (millitesla) strength oscillating magnetic field, from a few megahertz to tens of gigahertz while operating on the < 200 milliwatt power budget of our microscope to avoid sample heating under operation at 4.2 kelvin. The CPWs were designed and simulated (Sonnet) to have a 50-Ω characteristic impedance.
throughout the device. With this design constraint, the waveguides could be coupled via multiple wire bonds to a ceramic coplanar waveguide board equipped with SMA connectors for use with commercial radiofrequency (rf) and microwave (MW) signal generators. To achieve the millitesla rf magnetic fields necessary to invert nuclear spin polarization and microtesla MW magnetic fields required to saturate electron spin resonance, the coplanar waveguides were designed to maintain a 50-Ω impedance while the centerline tapered from a 480 µm wide wire with a 230 µm wide gap to a 5 or 10 µm wide wire with a 3 µm or 6 µm wide gap, respectively. This constriction generated a high current density in the microwire capable of producing magnetic fields up to 5 millitesla for rf waves and a few microtesla for MW frequency irradiation with just 200 mW of input power. Additionally, this coplanar waveguide has demonstrated losses of just a few milliwatt across the device meaning sample, heating at cryogenic temperatures is negligible.

Furthermore, patterned silicon gridlines, seen above and below the CPW microwire in Figure 2, have been implemented into the ground plane of the coplanar waveguide to assist in the alignment of the cantilever and microwire under vacuum at temperatures down to 4.2 kelvin. Additional optical features may be added in future biological imaging experiments to rapidly locate specific molecules of interest.

In addition to using CPWs coupled to commercial frequency generators as a universal sample platform, we have further developed coplanar waveguides to be coupled to cryogenic chip scale microwave sources developed by Prof. Ehsan Afshari and coworkers (Figure 3). Coupled to our coplanar waveguides, these 36 GHz CMOS oscillators generate > 300 µW of output power at temperatures down to ~ 12 kelvin. Simulations show that this should be sufficient to saturate electron spin resonance in our magnetic resonance force microscope. This unique combination of CMOS oscillator and coplanar waveguide would be the first of its kind integrated into any cryogenic scanned probe microscope experiment.

References: