PROCEEDINGS OF SCIENCE

A "cheap" VNA for polarization determination

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This report verified DG8SAQ VNWA 3 vector network analyzer (VNA) for polarization measurement of solid-state targets. Comparative measurements between the VNA and the Bochum NMR module were performed. Two radiation-doped samples ^{6}LiD and NH_3, as well as the chemically TEMPO-doped sample material n-Butanol are polarized and measured at temperatures of 1 Kelvin and magnetic field strengths of 2.5T. The method of dynamic polarization is used to increase the degree of polarization. We achieved polarization values from less than one percent to up to 11%. Polarization measurement showed the extent to which a cheap VNA can be used as a Q-meter. The two measuring systems were connected via an electronic switch to the LC-circuit, so that alternating measurements of NMR spectra could be taken. The area under the NMR signals as well as the polarization values obtained from a TE calibration were compared between the two measuring systems. We showed that VNA has a linear behavior in determining the signal areas compared to the Bochum NMR module. Due to a low SNR for TE-signals differences of 2 percentage points arise for the determined maximum polarization values.

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1. Introduction

Dynamically polarized nucleon targets are used in (double) polarization experiments, such as the COMPASS experiment at CERN or the experiments at the Crystal-Ball at MAMI in Mainz or the Crystal-Barrel experiment at ELSA Bonn. The nucleon polarization is determined using the nucleon magnetic resonance (NMR) technique. The measurement is based on the Q-meter technology. The so-called Liverpool box is the most widely used Q-meter worldwide [1,2].

This report compares polarization measurements with the Bochum NMR module and the low-price vector network analyzer (VNA), respectively [8]. The study was initiated after the talk of Elena Long, PSTP2019, Knoxville [3].

2. Q-meter principal

The polarization of solid-state targets $P=(N\uparrow-N\downarrow)(N\uparrow+N\downarrow)$ is usually determined with a Q-meter. The voltage of a resonant circuit is measured in the Larmor frequency range. The target material is placed in or around the coil of the oscillating circuit and modifies the coil's inductance depending on the polarization. In our case, the coil is placed in the evaporator refrigerator and is connected to the capacitor in the tuning box with a transfer cable. This (coaxial-) cable is also called lambda/2 cable because it is a multiple of half a wavelength of the exciting frequency.

The voltage across the circuit depends on the polarization and is proportional to that of the integral of the NMR signal:

$$P=k\int_0^\infty \chi''(\omega)d\omega$$

The constant k summarizes all constants of the nuclear system and the electronics. The proportional relationship between the polarization of the target material and the integral of the

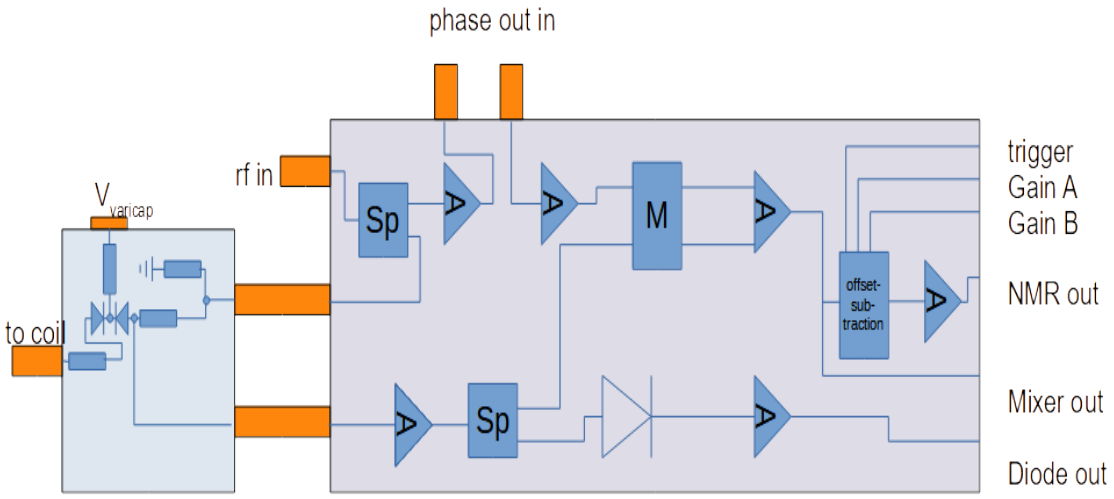

Figure 1: Schematics of the Bochum NMR module. The smaller box on the left is the tuning part with a constant current resistor and a varicap diode. The right side part consists of a diode detector and a phase-sensitive detection.

absorption part χ'' is valid. The integral can also be interpreted as the area below the resonance line. More details can be found in [4].

2.1 Bochum NMR module

The Bochum NMR module [5,6] is based on the Liverpool NMR module [1,2]. The basic structure is similar. However, the tuning capacitor and constant current resistor were removed and placed in an additional case. As a result, the capacitor is closer to the refrigerator and the transfer cable, and thus, its electronic losses are reduced. A BB212 varicap diode was installed as a capacitor, which allows the resonant circuit to be automatically tuned. The voltage across the oscillating circuit is amplified with low-noise amplifiers and can be rectified using diodes or a phase-sensitive detector before it is further amplified. Figure 1 shows a schematic of the Bochum NMR module. For further information, see [5,6].

2.2 Vector Network Analyzer

A vector network analyzer (VNA) is an electronic instrument used for measuring the performance of radio frequency (RF) and microwave devices, components, and systems. It transmits a known signal into the device under test (DUT) and measures the reflected and transmitted signals using two receivers. The VNA then calculates the complex scattering parameters (S-parameters) of the DUT. S-parameters describe how the device behaves at different frequencies.

S-parameters can be used to determine important characteristics of the DUT, such as impedance, bandwidth, and gain, and can also be used to design and optimize RF and microwave systems. VNAs are used in various applications, including telecommunications, radar systems, and high-speed data communications.

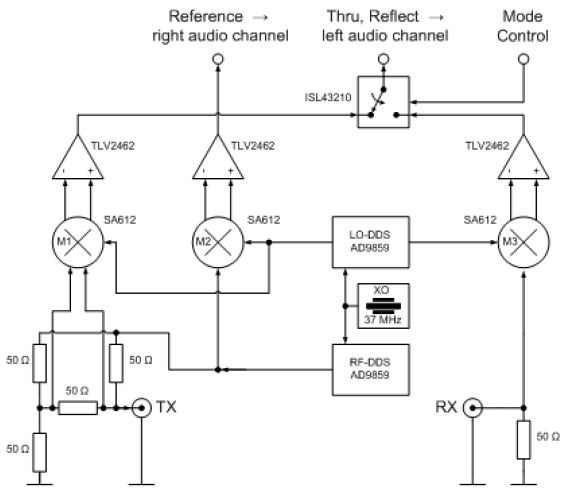

Figure 2: Basic structure of a vector network analyzer[7].

S-parameters are a set of complex numbers used to describe the behavior of linear electrical networks, such as RF and microwave components, over a range of frequencies. They are typically represented as a matrix, with each element denoted by S_{ij}, where i and j refer to the input and output ports of the network, respectively. The S-parameters describe the amplitude and phase of the signals transmitted and reflected by the network, as well as the impedance mismatch between the network and the source and load.

They are commonly used in the design and analysis of RF and microwave systems, as they can be used to predict the performance of components and networks, such as filters, amplifiers,

and antennas, and to optimize system performance. In our case, we measure the amplitude of the oscillating circuit and determine the area under the signal proportional to the polarization.

In our setup, the DUT consists of a tuning-box connected to the NMR coil via a transfer cable. For preamplification, an additional low-noise amplifier is placed between the tuning box and the RX of VNA (Figure 3). Next, we extracted the signal amplitude. The scattering parameters of interest are the reflection S_{11} and transmission S_{21}.

2.3 Setup and measurements

The NMR module is coupled to the sample alternately with the VNA using a switch. Hence, we generate a quasi-parallel measurement of the polarization. The resonant circuit is tuned to the Larmor frequency with the respective tuning box for both configurations. Figure 3 shows the experimental setup.

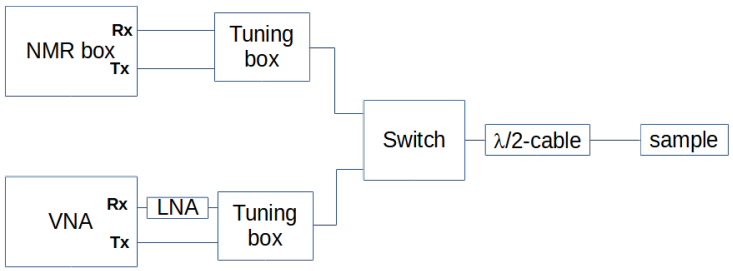

Figure 3: Experiment setup[8].

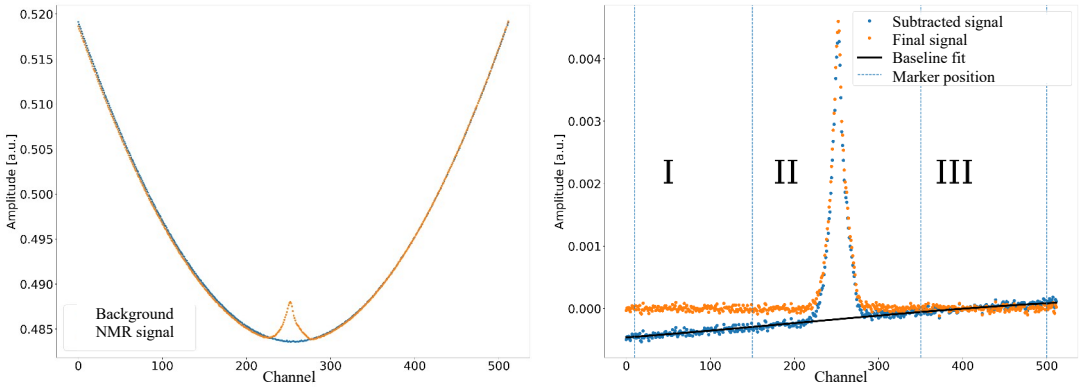

Figure 4: Signal processing. Left, raw and background signal. Right, subtracted signal with fitted polynomial baseline.

The measured signals (raw signal) are further processed for evaluation: The background signal, recorded at a magnetic field outside the NMR condition, is subtracted from the raw signal. A 3rd-degree polynomial is then fitted to the baseline outside of the NMR signal of the spectrum obtained (Figure 4, I and III) and subtracted from the spectrum. Finally, the actual signal can be integrated and compared for both systems.

The measurements were made with a ^{4}He evaporator at $77\,K$ and $1\,K$ and $2.5\,T$. ^{6}LiD, NH_3 and n-Butanol were used as target materials. The absolute polarization and the

relative integral of the signals of both systems were compared. The absolute polarization value was determined with the thermal equilibrium (TE) method.

The first measurements were made with ^{6}LiD at liquid Nitrogen temperatures ($77\,K$) and $B=2.5\,T$. At $77\,K$ only the dynamic polarized signals can be obtained and show a constant ratio. Figure 5 shows the result for both systems and the area-units of the VNA are scaled for a better comparison. The next measurements were performed at $T=1\,K$ and $B=2.5\,T$.

Figure 6 shows the TE signals for n-Butanol in both systems. The VNA's signal-to-noise-ratio (SNA) is worse, making precise TE calibration difficult. The values are running parallel when comparing the dynamic area units of the two systems for n-Butanol at $1\,K$ and $2.5\,T$ (see Figure 7 left). After the TE-calibration the polarization values of the two measuring systems (see Figure 7 on the right), deviate by 20% relatively. Similar behavior can also be observed with NH_3 values (not shown). Further measurements with ammonia and linearity tests are presented in detail in Florian Grimm's Master thesis [8].

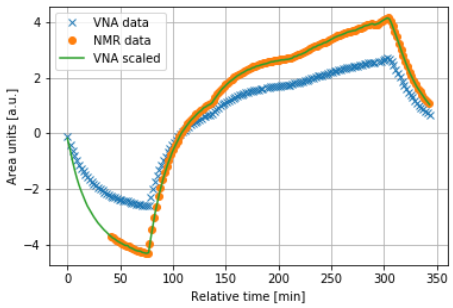

Figure 5: Area units timeline of ^{6}LiD at 77K and 2.5T

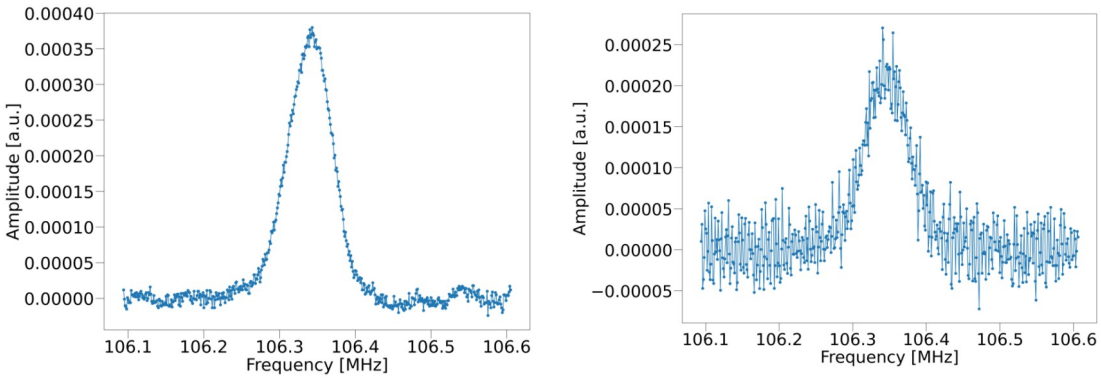

Figure 6: TE signals of n-Butanol at $1\,K$ and $2.5\,T$ measured with Bochum NMR module (left) and VNA (right).

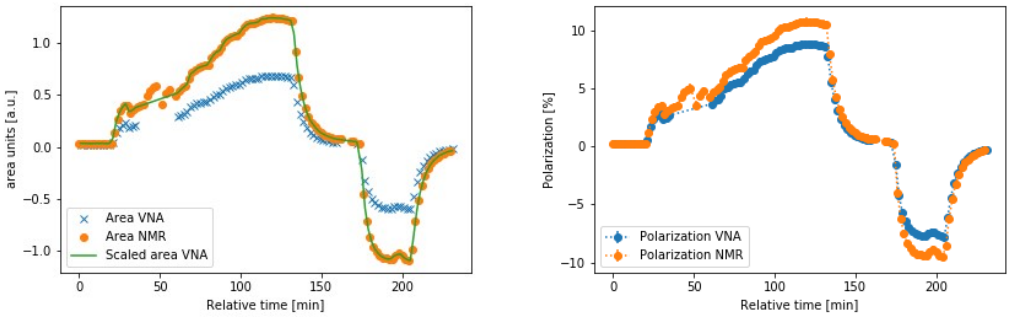

Figure 7: n-Butanol: Area units vs time (left), polarization vs time (right)

3. Conclusion

The measurements of the various sample materials were obtained at a magnetic field of $B = 2.5\,T$ and temperatures of $T = 77\,K$ and $T = 1\,K$ in a ^{4}He evaporator. The measuring apparatus comprises the alternating determination of the areas of the NMR signals with the two Q-meter systems. Signals in thermal equilibrium and during dynamic nucleon polarization were recorded. A comparison of the areas of the measured signals showed good agreement for all sample materials and also for both measurement setups. The proportionality of the measured values with the VNA and the NMR module shows a good agreement. In addition to a comparison of the areas, a polarization determination was also carried out for NH_3 and n-Butanol via the TE calibration. VNA's TE signals were overlaid by more noise than NMR module TE signals. However, since the determination of the TE areas is an integral part of the polarization determination, these measurements led to deviations between the polarization values of the two measurement systems.

We conclude that the VNA for polarization measurement is limited. In addition to determining the polarization via the TE calibration, the polarization can also be obtained by determining the R ratio of quadrupole-broadened deuteron spectrum. This method provides an opportunity to check the linearity behavior of the VNA independently of other measuring systems. Subsequent measurements using this method could thus provide further information on the suitability of the VNA for polarization measurements.

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