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Shaping EPR: Phase and amplitude modulated microwave pulses

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ABSTRACT

The advent of fast arbitrary waveform generators in the sub-nanosecond time regime recently enabled new experimental developments in the field of pulsed EPR. In this article, the new possibilities of such fast phase/amplitude modulated microwave pulses are shortly described with respect to applications in pulsed dipolar spectroscopy. Some of the specific challenges of an accurate creation of such pulses in the field of EPR are outlined. Finally, a short outlook of potential applications is given and some specific experimental conditions are discussed, where shaped pulses might have an especially important impact in the future.

1. Introduction

Shaped excitation pulses or composite pulses have a long history in NMR (nuclear magnetic resonance) spectroscopy and imaging [1–6], but only very few examples [7–10] exist in the field of EPR (electron magnetic resonance) before 2012. There are many reasons for this, one results from the much more demanding technical requirements for EPR compared to NMR. In the case of EPR experiments, the excitation frequencies are in the microwave (MW) region compared to radiofrequencies (RF) in NMR. Typical rectangular pulse lengths for EPR are in the 5–100 ns regime compared to microseconds in NMR, whereas optimal repetition times for pulses in EPR experiments (and therefore also the times for acquisition of the signals) can be as short as 100 μs. This is again order of magnitudes faster compared to NMR. The origin for this lies in the 658 times larger magnetic moment of the electron spin compared to a proton nuclear spin. The demand of fast MW switching (phase and amplitude) devices as well as the need for fast signal acquisition and averaging devices restrained pulsed EPR applications much more compared to the field of NMR. Only recently, and due to applications in communication technology, versatile arbitrary waveform generators (AWG) with a fast enough sample rate, memory size and dynamic range for pulsed EPR applications became available (and affordable). The Prisner and Glaser groups performed a first demonstration [11] using optimum control theory (OCT) derived pulses originally developed for the field of NMR [12]. It could be shown that an OCT-derived excitation pulse with a bandwidth of 200 MHz offered improved performance for Fourier-transform (FT) EPR on radicals in solution. The hyperfine pattern obtained with OCT-derived pulses resembled the cw-EPR spectrum much better compared to experiments performed with classical rectangular pulses and the same MW field strength. This encouraged several research groups worldwide to explore the potential of shaped pulses for EPR applications. Most of this work has been reviewed recently [13,14]. Therefore, only some specific applications of shaped pulses for measuring the dipolar coupling between two unpaired electron spins, called pulsed dipolar spectroscopy, will be mentioned in this article.

Chirp and sech/tanh pulses were used to improve pulse EPR sequences for measuring the dipolar interaction between two paramagnetic centers. For example, it could be shown that for PELDOR/DEER experiments increased modulation depths can be achieved by using a chirp or sech/tanh pump pulse [15,16]. The Jeschke group performed extensive work devoted to pulsed dipolar spectroscopy using high-spin (S = 7/2) Gd(III) spin labels [17,18]. In this case chirp-pulses can also be used to increase the population of the central transition ($m_s = -1/2 \leftrightarrow +1/2$) by polarization transfer from the other electron spin levels. Whereas in these cases the increased bandwidth of adiabatic inversion pulses is of most importance, the more homogeneous inversion profile of adiabatic pulses within a defined bandwidth is beneficial to extend the PELDOR/DEER sequences to Carr-Purcell pulse trains. Such sequences prolong the dipolar evolution time window, allowing determination of longer distances [19,20]. Fast passage pulses can be used to generate ultra-wideband transversal magnetization [21]. Such

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pulses improved strongly the performance of the SIFTER (Single Frequency Technique for Refocusing Dipolar Couplings) pulse sequence [22] by exciting the whole nitroxide spin spectrum at X-band and Q-band frequencies [23,24]. The possibility to excite the whole nitroxide spectrum with such pulses allows performing 2-dimensional experiments similarly to NMR, where the direct dimension encodes the spectral information [25]. This is important for spin labels rigidly attached to a biomolecule for extracting angular information from the spectrally resolved dipolar time traces [26].

2. Challenges

Fast phase/amplitude modulated excitation pulses with a possible bandwidth of 200 MHz up to 1 GHz offer the possibility to excite the complete inhomogeneously broadened EPR line of most organic radicals, as for example nitroxide spin labels, and can strongly improve the excitation efficiency of other paramagnetic species. Some typical examples of paramagnetic species with their respective spectral widths are shown in Fig. 1. Such broadband homogeneous excitation cannot be achieved with rectangular MW pulses; even a rectangular π pulse with a length of only 8 ns results in a non-homogeneous inversion profile over a bandwidth of 200 MHz (see Fig. 2).

One major challenge using broadband shaped pulses in EPR arises from the MW resonators. In pulse EPR experiments the MW resonator bandwidth $\Delta\omega$ is tuned to match the excitation bandwidth (or the time scale) of the MW pulses. This resonator bandwidth is defined by the resonator quality factor Q_R by:

$$Q_R = \frac{\omega_{MW}}{\Delta\omega} \tag{1}$$

Indeed, the shape of the MW resonator profile usually smoothens the sharp edges of the rectangular MW pulses, leading to a reduction of the sin(x)/x sidebands of truly rectangular pulses [27]. The resonator quality factor also amplifies the achievable MW field strength ω_1 by:

$$\omega_1 = c\sqrt{Q_R P_{MW}} \tag{2}$$

with c being a conversion factor specific to the geometry of the used MW resonator and P_{MW} being the applied MW power.

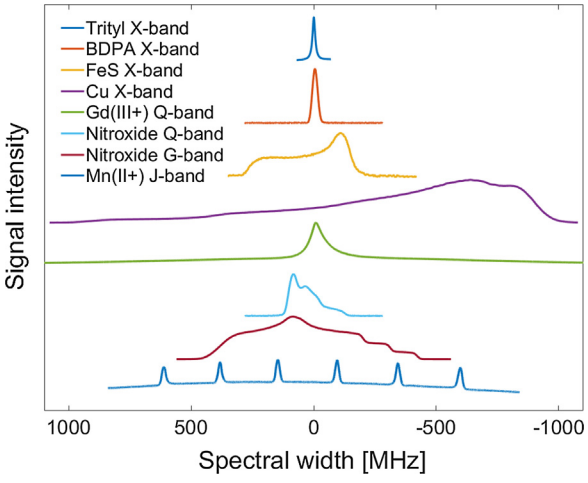

Fig. 1. EPR spectral shapes of some radicals detected at different MW frequency bands, corresponding to different magnetic field strengths (X-band: 0.3 T, Q-band: 1.2 T, G-band: 6.4 T, J-band: 9.4 T). The spectra are shown in frequency units (MHz) for an easier comparison with the typical MW excitation profiles. The excitation bandwidth for rectangular pulses is typically below 200 MHz, whereas for shaped pulses the bandwidth can reach 1 GHz.

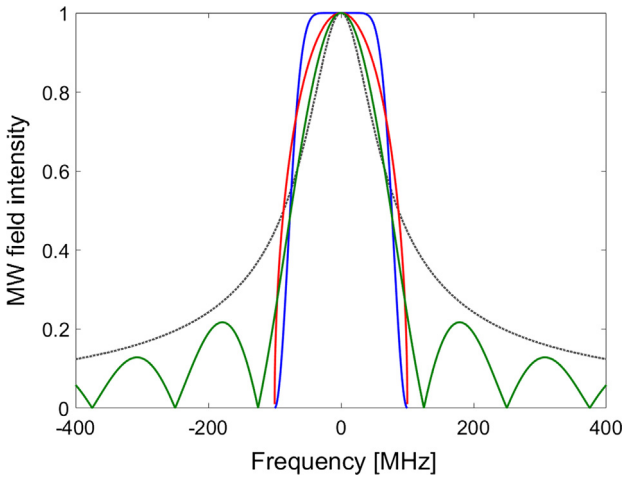

Fig. 2. Comparison of the frequency dependent excitation MW amplitudes of some pulses with the MW resonator profile for a bandwidth of 200 MHz (gray dotted line). Shown are the amplitude profiles for a WURST pulse (red), a sech/tanh pulse (blue) and the Fourier components or a rectangular pulse with a pulse length of 8 ns length. As can be seen, the resonator profile best fits to the frequency profile of a rectangular pulse. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

In the case of applying broadband shaped MW pulses with an increased excitation bandwidth $\Delta\omega$, the resonator bandwidth has to be wider (the resonator quality factor has to be smaller). This reduces the maximum achievable MW field strength ω_1 for these pulses compared to rectangular pulses. Additionally, the increased resonator bandwidth imposes a frequency dependence on the MW field strength ω_1, which interferes with the frequency-dependent amplitude profiles $\omega_1(\Delta\omega)$ of commonly used adiabatic pulses [2] (Fig. 2).

However, these profiles can be taken into account by performing offset-dependent Rabi nutation experiments to optimize chirped [15] or OCT-derived pulses [28]. Unfortunately, the resonator profile depends strongly on the sample used, the measurement temperature and varies even under same conditions from day to day. Therefore, this procedure has to be performed before each measurement. In any case the reduction of the resonator quality factor and the frequency offset dependent MW field strength $\omega_1(\Delta\omega)$ imposed by the resonator mode prolongs the pulse length of broadband shaped pulses, compared to rectangular pulses. Typically, rectangular inversion pulses are approximately 10–40 ns long for MW frequencies up to W-band (95 GHz). Adiabatic pulses in EPR are considerably longer, typically about 200 ns. This restricts experiments in two ways: First, experimental settings with broadband pulses suffer from the short transversal relaxation times T_2 of many paramagnetic species, which is typically in the low microsecond range or lower. Secondly, dipolar and hyperfine couplings in EPR are often larger than the inverse pulse length (5 MHz), leading to negative interference effects (averaging) of these coherent contributions in time traces if not special taken care of [29].

In addition, a resonator serves as a band filter for MW noise (N). The increase of the resonator bandwidth necessary to support broadband pulses therefore increases the noise level at the MW detector:

$$N \sim \sqrt{\Delta\omega} \tag{3}$$

All these restrictions by the MW resonator mentioned above only hold for classical MW resonators or EPR applications at lower MW frequencies (below 50 GHz). EPR Micro-resonators, developed for experiments with tiny samples, typically have a much larger

intrinsic bandwidth [30]. However, these resonators typically possess a large ω_1 inhomogeneity across the sample. In such cases, the gain achieved by broadband shaped pulses, which compensate for the distribution in ω_1 field strengths can be much larger. The same is true for MW resonators at high-field magnetic fields (larger than 3 T magnetic field). In these cases, loaded resonators have typically a quality factor of Q = 200–1000. Unfortunately, the MW power at these frequencies (larger than 90 GHz) is still limited, leading to typical rectangular pulse lengths in the 20–100 ns range. Therefore, at high magnetic fields the resonator bandwidth exceeds the excitation bandwidth of rectangular pulses. Again, broadband shaped pulses can easily improve the performance of pulsed EPR experiments at high magnetic fields, as has been demonstrated recently at 200 GHz [31] and 260 GHz [32]. At such high frequencies, already organic radicals show substantial broadened EPR spectra due to g-anisotropy, thus making broadband MW excitation very useful to achieve substantially inversion or excitation efficiencies. Additionally, it is much more demanding and difficult to achieve high quality phase settings at such high frequencies with classically generated MW pulses (switching of a fixed frequency). AWG-generated MW pulses give a much better accuracy and control of phase and amplitude at such high frequencies, despite the more complicated non-linear upconversion process of the AWG modulated pulses [31,32].

A simplification, arising from the high-field approximation, might also be helpful for designing and using broadband pulses. At X- and Q-band frequencies, solid-state EPR spin systems are often a complicated admixture of different anisotropic interactions (as hyperfine and quadrupole interaction, g-tensor and zero-field-splitting). This considerably complicates the spin Hamiltonian and makes optimization of pulse sequences for instance with OCT rather complicated [11,29]. At high magnetic fields the electron spin Hamiltonian becomes simpler, having the g-anisotropy as the dominant anisotropic interaction. Selecting different g-values with the excitation pulses might lead to an almost isotropic coupling situation with straightforward implementation of OCT sequences optimized for NMR experiments [33].

3. Perspectives/outlook

Within the last 10 years, broadband shaped pulses found their way into the field of EPR due to the availability of fast AWGs. Such devices are nowadays already an integral part of commercial pulse EPR spectrometers from Bruker. Nevertheless, looking on the recently published biological applications of pulsed EPR, the use of shaped pulses is still an exception. What is the reason for that? It is possible that it just takes some time until new methods get established, as Planck already stated in his autobiography [34]: *New scientific findings do not become commonly accepted by convincing other scientists, but rather by waiting until they have died and a new generation of scientists immediately starts with it.* More seriously, I think that the lack of application of shaped pulses in structural biology EPR might be related to the simplicity to visualize and understand the action of rectangular pulses on the spin system. We all understand the action of rectangular fixed-frequency pulses on spins in the rotating Bloch frame. This becomes less obvious for pulses with amplitude and phase modulation. Numerical simulations cannot replace this simple imagination, which of course is only exactly valid for an isolated spin S = ½. This is not so easily done for shaped pulses, for example generated by OCT. This more complicated behavior of shaped pulses is reflected in more parameters describing such pulses, leading to more difficult experimental optimization procedures of such pulses. Whereas it is rather easy to optimize rectangular π/2 and π pulses, for example with a simple Hahn echo sequence, this is not as easily done for shaped pulses. Already the optimal shape of the expected echo signal is different; whereas with classical rectangular pulses typically a narrow hole, solely determined by the pulse excitation profile, is burned into the inhomogeneous broadened EPR line, signals from broadband pulses depend much more on the shape of the EPR line, which has to be taken into account for optimization. This is sketched for the echo signal of a nitroxide radical at X-band frequencies in Fig. 3, where the broadband WURST pulses are optimized for optimal coverage of the spectral shape of nitroxide radical important for orientation selective SIFTER experiments. Experimentally we found in our group that pulses of equal length perform in this respect better than the Bohlen-Bodenhausen [6] scheme [14,26].

For amplitude and phase modulated pulses, more parameters have to be optimized and more experimental restrictions, such as resonator behavior or amplifier linearity, have to be taken into account. Rectangular π/2 and π pulses are rather robust in this respect: the resonator profile fits well to the excitation efficiency (see Fig. 2) and both rectangular pulses are rather amplitude insensitive at their optimal settings, because of the flat slope of the cosine function at maximum. Despite the fact, that adiabatic pulses have superior broadband inversion behavior more optimization parameters have to be adjusted for pulse sequences and for a given target function, as explained above. In this respect, the EPR community can learn again from the NMR community, where such pulses are implemented and used for some time.

Setting up standard procedures how to adjust broadband pulses for optimal performance will be an important step forward for their usage in routine applications. I believe that if this is accomplished many more EPR applications will take advantage of the improved performance of shaped pulses. One field where the gain of such pulses seems obvious and promising, is high-field pulsed EPR and DNP [35], as explained above. Here, the implementation of the AWG is more demanding (because of the non-linear upconversion process of the MW), but worthwhile. Broadband shaped

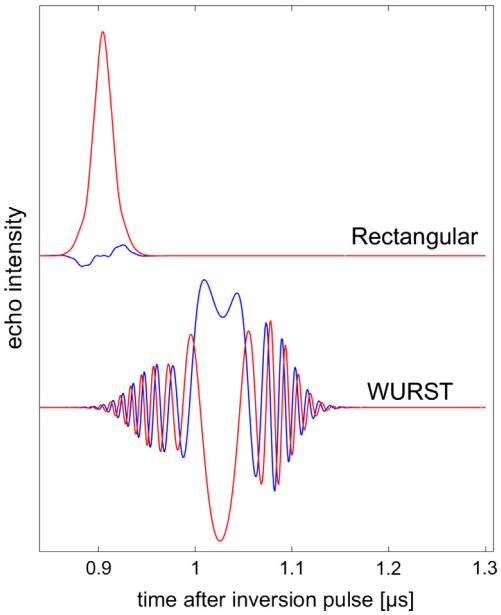

Fig. 3. Hahn echo signal of a nitroxide radical at X-band frequencies achieved with: (upper traces) rectangular pulses (14 ns π-pulse length) or (lower traces) broadband WURST chirped pulses of 250 ns length and a bandwidth of 200 MHz with the same maximum B_1 field strength as for the rectangular pulses. Shown are both phase components of the IQ detection mixer (in red and blue). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

MW pulses might not be able to excite the whole EPR spectra of most paramagnetic species at high frequencies, because of the large spectral width induced by the g-anisotropy. However, the possibility to excite selective specific portions of the spectrum with shaped pulses with rather homogeneous flip angles is a big advantage when composing more demanding pulse sequences and simplifies analyzing orientation-selective couplings [36]. The same argument also holds for many inorganic paramagnetic species at low fields. Quantum computing is another field, which profits already a lot from the precise manipulation of electron spins with shaped pulses [37]. The use of AWG shaped MW pulses can also be a large advantage for setting up a benchtop DEER spectrometer for applications in structural biology. Not only it is easier, accurate and cheap to create two-frequency pump and probe pulse sequences this way; the possibility to create automatic tuning and calibration procedures [38] can potentially be a big advantage for making such instruments accessible by non-expert users. Additionally, the control of the phase by an AWG allows more easily and accurate to perform phase cycling and amplitude modulation alone already can improve experiments, for example by Gaussian pulses [9,10,39]. Finally, it is a lot of fun to play around with the new possibilities that AWG shaped MW pulses offer. I strongly believe that this curiosity will create in the future many new pulse sequences and experiments, so far not accessible for EPR.

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