Frequency-modulated pulses for quantum bits coupled to time-dependent baths

Benedikt Fauseweh,1,‡ Stefano Pasini,2,† and Götz S. Uhrig1,‡

1Lehrstuhl für Theoretische Physik I, TU Dortmund, Otto-Hahn Straße 4, DE-44221 Dortmund, Germany
2Forschungszentrum Jülich, DE-52425 Jülich, Germany

(Received 2 December 2011; published 7 February 2012)

We consider the coherent control of a quantum bit by the use of short pulses with finite duration \( \tau_p \). By shaping the pulse, we perturbatively decouple the dynamics of the bath from the dynamics of the quantum bit during the pulse. Such shaped pulses provide single quantum bit gates robust against decoherence which are useful for quantum-information processing. We extend previous results in two ways: (i) we treat frequency-modulated pulses and (ii) we pass from time-independent baths to analytically time-dependent baths. First- and second-order solutions for \( \pi \) and \( \pi/2 \) pulses are presented. They are useful in experiments where amplitude modulation is difficult to realize.

DOI: 10.1103/PhysRevA.85.022310 PACS number(s): 03.67.Pp, 82.56.Jn, 76.60.Lz, 03.65.Yz

I. INTRODUCTION

The occurrence of decoherence in quantum systems is one of the main difficulties to be overcome in modern experiments. Especially quantum-information processing (QIP) requires the quantum system to remain in fixed phase relations between the application of quantum gates. Otherwise one cannot benefit from the quantum parallelism making QIP such a powerful technique.

A generic example for a quantum bit (qubit) is a spin \( S = 1/2 \). One of the first implementations of a quantum algorithm was realized with nuclear magnetic resonance (NMR) [1]. The qubits are encoded in the nuclear spin degrees of freedom. We also use the spin language to describe the states and dynamics of the qubit. The state \( \uparrow \) is identified with the logical \( |1\rangle \) and the state \( \downarrow \) with the logical \( |0\rangle \).

The loss of coherence is induced by the coupling of the spin to its environment, the so-called bath. One way to suppress this coupling is the application of suitable control pulses first introduced by Hahn in 1950 [2] for NMR experiments. This idea led to the development of sequences for control pulses ranging from the Carr-Purcell-Meiboom-Gill (CPMG) cycle [3,4] to more and more complex control schemes [5]. In QIP, this approach is known under the name of dynamic decoupling (DD) [6–8]. Theoretically, dynamic decoupling can be achieved to infinite order in the duration \( T \) of the total pulse sequence [9,10]. One particularly efficient way to deal with pure dephasing decoherence is the use of theoretically optimized DD (Uhrig DD) [11–13]. It has been successfully implemented experimentally [14,15].

The pulses considered in theoretical studies of DD schemes are mostly ideal in the sense that they have an infinite amplitude and that they act instantaneously in time corresponding to Dirac \( \delta \) pulses. Of course, this property cannot be realized in experiments. If the finite pulse duration is taken into account in calculations, it turns out to be a nuisance in most cases (see, for instance, Refs. [10,16]). Hence, there is an abundant literature on pulse shaping and optimization which we can mention only partly [16–31] (for a book see Ref. [32]). We emphasize, however, that a suitably shaped pulse can be integrated into a DD sequence such that the high-order suppression of decoherence is hardly hampered [33,34].

The majority of the existing theoretical studies of pulse shaping consider pulses acting on the two-dimensional Hilbert space. The goal is to design robust pulses which tolerate a maximum of frequency offset or other inaccuracies of the pulse [17–23,26]. The next stage of complexity includes random time-dependent classical noise, which is still described by classical fields coupled to the spin [25]. The maximum stage of complexity considers a fully quantum mechanical bath which means that the qubit is coupled to a macroscopic quantum mechanical system by noncommuting operators [16,24,27–31]. It is on this level that our present study is situated. We stress that a quantum mechanical pulse, which is robust against a coupling to its environment, constitutes an appropriate single-qubit gate.

In particular, we extend previous work [30] in two ways: (i) We allow for analytically time-dependent bath operators, both in the spin-bath coupling and in the Hamiltonian of the bath. Such time dependence may, for instance, arise from a time-dependent reference frame [35]. (ii) We propose frequency-modulated pulses while before only amplitude-modulated pulses were studied [16,24,27,28,30,31] except in the general no-go theorem in Ref. [29]. We stress that in the NMR context amplitude and phase-modulated pulses have been discussed intensively [21–23]. But to our knowledge these investigations do not comprise quantum mechanical baths nor dynamic classical noise.

Explicitly, we compute continuous solutions for \( \pi \) and \( \pi/2 \) pulses realized by frequency modulation (see also Ref. [23]). The consideration of frequency modulation is motivated from experimental situations where the frequency of a pulse can be controlled more accurately or more easily than its amplitude. Thus the present study is complementary to preceding ones.

The paper is organized as follows: In Sec. II, we give an overview of the model under study and motivate our ansatz for the time evolution of the whole system. In Sec. III we derive the perturbative expansion for a generic time-dependent bath. We require that the time dependence is analytical in order to be able to apply a perturbative approach. Then we introduce the frequency-modulated ansatz in Sec. IV and specialize the
general equations for this specific case. The solutions found for first- and second-order pulses are discussed in Sec. V and we finally conclude in Sec. VI.

II. MODEL AND ANSATZ

We consider the general case of a spin coupled to a time-dependent bath

\begin{equation}
H(t) = H_0(t) + \hat{\sigma} \cdot \hat{A}(t),
\end{equation}

where \(H_0(t)\) denotes the part of the Hamiltonian that acts only on the bath. We refer to it as the bath Hamiltonian. The vector of Pauli matrices \(\hat{\sigma}\) acts on the Hilbert space of the spin \(S = 1/2\) while \(\hat{A}(t)\) is a vector of bath operators to which the spin is coupled. No special operator structure is assumed for the bath operators; i.e., the commutators \([A_i(t'), A_j(t)]\), \([\hat{A}_i(t'), \hat{A}_j(t)]\), and \([A_i(t'), H_0(t)]\) do not need to vanish.

The model (1) comprises typical cases such as a bosonic bath or a spin network. Relevant experimental systems comprise the electronic spin in a quantum dot coupled to the bath of nuclear isotope spins [36] or the spin of a nitrogen vacancy center in diamond interacting again with a bath of nuclear isotope spins [37]. For our purposes, we require that the time dependence of the operators \(H_0(t)\) and \(\hat{A}(t)\) is analytical so that they can be expanded in time:

\begin{align}
\hat{A}(t) &= \hat{A}_0 + \hat{A}_1 t + \hat{A}_2 t^2 + \cdots, \\
H_0(t) &= H_{0,0} + H_{0,1} t + H_{0,2} t^2 + \cdots.
\end{align}

This analyticity is often fulfilled, e.g., in rotating reference frames or in the operator interaction picture. For fast time-dependencies, however, the above expansion is not useful because the derivatives are large. Very fast oscillatory time-dependencies are better treated by average Hamiltonian theory.

Our model includes the common case of a purely dephasing bath, i.e., a spin coupled only along the \(\sigma_z\) direction to the bath. This model is justified in experiments where the dephasing time \(T_\perp\) is significantly lower than the longitudinal relaxation time \(T_1\). This is the case if the energetic splitting between the states with \(\sigma_z = 1\) and \(\sigma_z = -1\) is large.

The coupling strength between the spin and the bath is given by \(\lambda := ||\hat{A}(t)||\) while the energy of the bath is defined to be \(\omega_0 := ||H_0(t)||\). If these operators are not bounded, that means if \(\lambda\) and \(\omega_0\) cannot be defined by the operator norms, we refer by \(\lambda\) and \(\omega_0\) to the generic energy scales of the corresponding operators. For instance, in a bosonic bath \(\omega_0\) is the upper cutoff of the bosonic energy spectrum. The energy scales serve as reference values for \(\tau_p\). That means that we aim at an expansion in the dimensionless ratios \(\omega_0 \tau_p\) and \(\lambda \tau_p\).

Applying the control pulse to the system, the term

\begin{equation}
H_0(t) = \hat{\sigma} \cdot \vec{v}(t)
\end{equation}

starts at \(t = 0\) and ends at \(t = \tau_p\). The time evolution between 0 and \(\tau_p\) of the combined system reads

\begin{equation}
U(t) = T \left[ \exp \left( -i \int_0^t H(t) dt - i \int_0^\tau H_c(t) dt \right) \right],
\end{equation}

where \(T\) stands for the standard time ordering.

Our aim is to perturbatively decouple the time evolution of the spin from the time evolution of the bath during the pulse. This motivates the following ansatz for the time evolution of the whole system

\begin{equation}
U(\tau_p) = U_h(\tau_p) P(\tau_p) U_c(\tau_p),
\end{equation}

where

\begin{align}
U_h(\tau_p) &= T \exp \left( -i \int_0^\tau H_0(t') dt' \right), \\
P(\tau) &= T \exp \left( -i \hat{\sigma} \cdot \vec{v}(t) dt \right).
\end{align}

The unitary operator \(U_h(\tau_p)\) describes the time evolution of the bath and \(P(\tau_p)\) the rotation of the spin due to the pulse. Note that the ansatz \(U_h(\tau_p) P(\tau_p)\) does not comprise any coupling between spin and bath. It is close to the goals of many previous studies aiming at robust pulses [17–23,25,26] and it corresponds to the ansatz used in previous studies separating the pulse from a classical [25] or quantum mechanical dynamics of the bath [16,24,27,30,31]. We emphasize that this ansatz which separates the pulse from the dynamics of the spin plus bath system can be shown not to succeed beyond leading order [28,29].

Since the spin-bath coupling is not included in \(U_h(\tau_p) P(\tau_p)\) we introduced the correction unitary operator \(U_c(\tau_p)\) in Eq. (5). We want to shape the pulse so that the correction term is as close to the identity as possible. A perfect decoupling would imply \(U_c(\tau_p) = 1\). But this is unrealistic to achieve. Hence we pursue the perturbative approach to make as many terms of an expansion in \(\tau_p\) as possible vanish. Then \(U(\tau_p) \approx U_h(\tau_p) P(\tau_p)\) represents a valid approximation and one can neglect the spin-bath coupling during the pulse. We remark that pulses shaped in this way constitute robust single-qubit gates.

III. DERIVATION

The derivation of the perturbative conditions for the shaped pulses is very similar to the derivation given in Ref. [30]. Yet we present a brief outline here in order to keep the present article self-contained and because we extend the previous derivation to analytically time-dependent baths. We start from the pulse Hamiltonian in Eq. (3). We describe the time-dependent pulse operator as a global rotation about the axis \(\hat{a}(t)\):

\begin{equation}
P(t) = \exp \left( -i \hat{\sigma} \cdot \hat{a}(t) \frac{\psi(t)}{2} \right),
\end{equation}

where \(|\hat{a}(t)| = 1\). The spin is turned by the angle \(\psi(t)\) at the time \(t\). Every unitary operator acting only on the Hilbert space of the spin can be written in the form of Eq. (7). In particular, a pulse that turns the spin by an angle \(\chi\) satisfies

\begin{equation}
\psi(\tau_p) = \chi.
\end{equation}
We stress the difference between the current axis of rotation $\vec{v}(t)/|\vec{v}(t)|$ and the effective axis $\vec{a}(t)$ describing the total rotation of the spin from its position at time 0 to its current position at time $t$.

By definition the pulse operator fulfills the Schrödinger equation

$$i\partial_t P(t) = H(t)P(t), \quad (9)$$

which implies [29]

$$2\vec{v}(t) = \psi'(t)\vec{a}(t) + \vec{a}'(t)\sin\psi(t) - \left[1 - \cos\psi(t)\right]\left[\vec{a}'(t) \times \vec{a}(t)\right]. \quad (10)$$

This differential equation is solved numerically for the frequency-modulated ansatz below. The time evolution of the whole system is given by

$$i\partial_t U(t) = \left[H_0(t) + \vec{\sigma} \cdot \vec{A}(t) + H_\nu(t)\right]U(t). \quad (11)$$

Inserting the ansatz (5) and solving for $\partial_t U(t)$ yields

$$i\partial_t U(t) = G(t)U(t)$$

$$G(t) = \left[P^{-1}(t)U^{-1}_0(t)\vec{\sigma} \cdot \vec{A}(t)U_0(t)P(t)\right]. \quad (13)$$

Thus the unitary correction is determined by a Schrödinger equation with $G(t)$ as its time-dependent Hamiltonian. The formal solution of Eq. (12) in terms of the standard time ordering operator is

$$U(t) = T\left[\exp\left(-i \int_0^t G(\tau)d\tau\right)\right]. \quad (14)$$

Aiming at an expansion of $U(t)$ in powers of $\tau_p$, it is convenient to use the Magnus expansion [38] to express the time-ordered exponential

$$U(t) = \exp[-i \tau_p(G^{(1)} + G^{(2)} + \cdots)], \quad (15)$$

where $G^{(i)} = O(\tau_p^{-i})$. The first two terms read

$$\tau_p G^{(1)} = \int_0^{\tau_p} dt G(t), \quad (16a)$$

$$\tau_p G^{(2)} = -\frac{1}{2} \int_0^{\tau_p} dt_1 \int_0^{t_1} dt_2 [G(t_1), G(t_2)]. \quad (16b)$$

Next, we need an expansion of $G(t)$ in powers of time. To this end, we consider the representation (7) which implies

$$P^{-1}(t)\vec{\sigma} \cdot \vec{A}(t)P(t) = \left[\cos\psi \vec{A} - \sin\psi(\vec{a} \times \vec{A})\right] + (1 - \cos\psi)(\vec{a} \cdot \vec{A})\vec{\sigma}$$

$$= \vec{n}_{A0}(t) \cdot \vec{\sigma} \quad (17a)$$

$$= \sum_{i,j} n_{i,j}(t)A(t)_{i,j} \sigma_i, \quad (17c)$$

where the time dependencies on the right-hand side of Eq. (17a) are omitted to lighten the notation. The vector operator $\vec{n}_{A0}(t)$ is the vector $\vec{A}(t)$ after a rotation about the axis $\vec{a}(t)$ by the angle $-\psi(t)$. The corresponding rotation matrix $D_\psi(-\psi)$ is given by its matrix elements $n_{i,j}(t)$; for their explicit form see Appendix C. Due to the orthogonality of $D_\psi(-\psi)$ the moduli of all its matrix elements are bounded by unity.

Note that there are two different kinds of time dependence in Eq. (17b). On the one hand, the time dependence of $\vec{A}(t)$ becomes weaker and weaker as the pulse duration $\tau_p$ is taken to zero because we assume that $\vec{A}(t)$ is analytical. This is exploited below. On the other hand, the time dependence of the $n_{i,j}(t)$ scales with $\tau_p$, which means that $\vec{n}_{i,j}(\eta) := n_{i,j}(\eta \tau_p)$ is completely independent of $\tau_p$ because the pulse has to be completed at $t = \tau_p$ whatever the pulse duration is.

We proceed by introducing the vector operator $\vec{A}(t)$ and expanding it in powers of $t$:

$$\vec{A}(t) := \vec{U}_0^{-1}(t)\vec{A}(0)\vec{U}_0(t)$$

$$= \vec{\Lambda}_0 + i \vec{t} H_0 \vec{A}_0 + t \vec{\Lambda}_1 + O(t^2). \quad (18b)$$

Here the main differences to the derivation in Ref. [30] arises. In Ref. [30], the term proportional to $A(t)$ did not appear because the bath was considered to be time-independent. Using the vector operator $\vec{n}_{A0}(t)$ from Eq. (17b) we rewrite $G(t)$ concisely as

$$G(t) = P^{-1}(t)\vec{\sigma} \cdot \vec{A}(t)P(t) \quad (19a)$$

$$= \vec{n}_{A0}(t) \cdot \vec{\sigma}. \quad (19b)$$

This form of $G(t)$ can be expanded in powers of $t$ such that the neglected terms are of second order in $\tau_p$ for $t \in [0, \tau_p]$:

$$G(t) = \vec{n}_{A0} \cdot \vec{\sigma} + t \left[i \left[H_0 \vec{A}_0(t), \vec{n}_{A0} \cdot \vec{A}(t)\right] + \vec{n}_{A0} \cdot \vec{\Lambda}_1 \vec{\sigma} + O(t^2)\right]. \quad (20)$$

Note that the time dependence stemming from the pulse rotation is not expanded because it does not change on $\tau_p \rightarrow 0$. Physically this means that one can expand in $\tau_p H(t)$, i.e., in $\lambda \tau_p$ and in $\omega_b \tau_p$, but not in $\tau_p H(t)$ because the magnitude of $H(t)\tau_p$ is increased on $\tau_p \rightarrow 0$ to realize the desired pulse.

Inserting Eq. (20) in the terms of the Magnus expansion (16) eventually yields

$$U(t) = \exp[-i(\eta^{(1)} + \eta^{(2)} + \cdots)] \quad (21a)$$

$$\eta^{(1)} = \sum_i \sigma_i A_{i,0}(t_0) \int_0^{\tau_p} n_{i,j}(t)dt, \quad (21b)$$

$$\eta^{(2)} = \sum_i \sigma_i \left[\sum_j \eta^{(2)}_j + \eta^{(2)}_i\right] \quad (21c)$$

where $\eta^{(i)} \propto \tau_p^i$. Explicitly, one has

$$\eta^{(2)}_j = \sum_j \left[H_0 \vec{A}_0, A_{j,0}(t)\right] \int_0^{\tau_p} t n_{i,j}(t)dt, \quad (22a)$$

$$\eta^{(2)}_i = \sum_{l,m} \left[A_{i,0}, A_{m,0}\right] \int_0^{\tau_p} dt_1 \int_0^{t_1} dt_2 \sum_{j,k} \epsilon_{ijk} n_{j,k}(t_1) n_{k,m}(t_2), \quad (22b)$$

$$\eta^{(2)c} = \sum_{i,j \leq k} \left[A_{i,0}, A_{j,0}\right] \int_0^{\tau_p} dt_1 \int_0^{t_1} dt_2 \sum_{l,m} \epsilon_{ijkl} n_{i,k}(t_2) - n_{i,j}(t_2) n_{l,k}(t_1). \quad (22c)$$

In these equations the anticommutator $[\cdot, \cdot]$, and the completely antisymmetric Levi-Civita tensor $\epsilon_{ijk}$ appear.
indices $i,j,k,l,$ and $m$ take one of the values $x,y,$ or $z$. Most of the Eqs. (21b) and (22) are identical to those obtained in Ref. [30]. Only in $\eta^{(2)}$ does the time dependence of the bath appear additionally. It is encoded in the operators $A_{i,j}$, which are zero for a time-independent bath.

The second-order equations (22) do not show a dependence on pure bath terms of an order higher than $H_{b0}$. This means that the time dependence of the pure bath Hamiltonian is irrelevant up to second order. This is reasonable because even for a time-independent bath the actual bath dynamics induced from $H_{b}$ appears only in second-order conditions. This does not apply to the vector operator $A(t)$ which is already relevant in first-order pulses.

In the general case of a completely generic bath, all the expressions $\eta^{(\alpha)}$, $\alpha \in \{1,2a,2b,2c\}$, have to vanish in order to fulfill $U(t) = 1 + O(t^{2})$. The pulse shape determines the time evolution of the matrix elements $n_{i,j}$. Hence, in order to fulfill all the conditions the operator-independent integrals in Eqs. (21b) and (22) must disappear. The resulting 39 scalar equations are identical to those obtained in Ref. [30].

This is our first key result. It proves the applicability of the previously obtained pulses even in the presence of a nontrivial time dependence of the bath which may stem from special reference frames or from the interaction picture of fast modes. For specific cases, such as the pure dephasing model or if $[H_{b}(t),A(t)] = 0$ the number of scalar equations to be fulfilled for $U(t) = 1 + O(t^{2})$ is reduced significantly. Pulses with less complexity can be used. This is studied in the sequel.

IV. FREQUENCY MODULATED ANSATZ

To solve Eq. (10) we choose an ansatz for $\bar{v}(t)$. In this paper we focus on a frequency-modulated pulse acting only in the $\sigma_{x,\sigma_{y}}$ plane with a fixed amplitude $V_{0}$ := $|\bar{v}|$ and the current axis of rotation

$$\bar{v}(t) = \begin{pmatrix} V_{0} \cos[\Phi(t)] \\ V_{0} \sin[\Phi(t)] \\ 0 \end{pmatrix},$$

where $\Phi(t)$ is a time-dependent phase. Note the difference to pulses with a time-dependent amplitude and a fixed axis discussed, for instance, in Refs. [16,27,30]. We focus here on frequency modulation in complement to previous work because there may be experimental setups where frequency modulation is much easier (or more accurately) implemented than amplitude modulation. Note that the ansatz (23) assumes that the control pulse can be switched on instantaneously. Transients are assumed to be sufficiently steep to be taken as jumps. The consideration of continuous amplitudes and frequency modulation is left to future research.

To point out the relation of the ansatz (23) to the experimental realization in the laboratory framework we consider a spin with a Larmor frequency $\omega_{L}$ in the NMR language [39]:

$$H_{\bar{v}} = \frac{\omega_{L}}{2} \sigma_{z}.$$

Of course, this description is not restricted to nuclear spins. Any two-level system with an energy splitting can be considered. The control field is realized by applying a field perpendicular to the $\sigma_{z}$ axis rotating with the Larmor frequency:

$$H_{\text{rf}} = V_{0}[\sigma_{z} \cos[\omega_{\text{rf}} t - \Phi(t)] - \sigma_{y} \sin[\omega_{\text{rf}} t - \Phi(t)]] \quad (25)$$

We include a time-dependent phase $\Phi(t)$ to shape the pulse. Its derivative $\dot{\Phi}(t)$ is the deviation of the frequency from the Larmor frequency. In this sense Eq. (25) describes a frequency-modulated pulse. Next, $H_{\text{rf}}$ is transformed into the rotating framework in which $H_{\bar{v}}$ vanishes. Using the unitary time evolution induced by $H_{\bar{v}}$

$$U_{\text{rot}}(t) = \exp \left( \frac{i \omega_{\text{rf}}}{2} \sigma_{z} \right),$$

we obtain $H_{\text{rot}}(t) = U_{\text{rot}}^{-1} H_{\text{rf}} U_{\text{rot}}$, which reads

$$H_{\text{rot}}(t) = \begin{pmatrix} V_{0} \sin[\Phi(t)] \\ 0 \\ \sigma_{x} \end{pmatrix} \begin{pmatrix} \sigma_{x} \\ \sigma_{y} \\ \sigma_{z} \end{pmatrix} = \bar{v}(t) \cdot \vec{\sigma}.$$ (27)

In order to find $\dot{v}(t)$ and $\psi(t)$ appearing in the parametrization in Eq. (7) of the pulse one has to solve the differential equation (10). Because $\bar{v}(t)$ is a unit vector, it is convenient to describe it by two angles $\phi(t)$ and $\theta(t)$:

$$\bar{v}(t) = \begin{pmatrix} \sin[\theta(t)] \cos[\phi(t)] \\ \sin[\theta(t)] \sin[\phi(t)] \\ \cos[\theta(t)] \end{pmatrix}.$$ (28)

Solving Eq. (10) for the time derivatives of $\psi(t)$, $\phi(t)$, and $\theta(t)$, we find

$$\dot{\phi} = 2 V_{0} \sin \theta \left[ \sin \phi \sin \psi + \cos \phi \cos \psi \right], (29a)$$

$$\dot{\theta} = V_{0} \left[ \frac{\cos \phi}{\sin \theta} \sin(\phi - \theta) - \sin \phi \cos \theta \cos(\phi - \theta) \right], (29b)$$

$$\dot{\psi} = V_{0} \left[ \frac{\cos \phi}{\sin \theta} \cos \theta \cos(\phi - \theta) + \sin \phi \sin \theta \sin(\phi - \theta) \right]. (29c)$$

The seeming singularities for vanishing angles on the right-hand sides of Eqs. (29b) and (29c) have no physical reason, but they only result from the choice of spherical coordinates and from the chosen parametrization in Eq. (7). Note that the global axis of rotation $\hat{\bar{a}}$ is not uniquely defined if $\psi$ is a multiple of $2\pi$.

At the very beginning at $t=0$ the current axis of rotation $\bar{v}$ and the global one $\hat{\bar{a}}$ coincide. The former lies by construction in the $\sigma_{x,\sigma_{y}}$ plane. Hence we have the initial conditions

$$\lim_{t \to 0} \theta(t) = \frac{\pi}{2},$$

$$\lim_{t \to 0} \psi(t) = 0,$$

$$\lim_{t \to 0} \phi(t) = \Phi(0).$$

where the latter two equations represent our deliberate choice. Inspecting the limit $t \to 0$ one additionally finds

$$2 \partial \phi_{\mid t=0} = \partial \phi(\Phi(t)\mid_{t=0}) = 0,$$

$$\partial \theta_{\mid t=0} = 0.$$ (31b)
The derivative \( \dot{\psi} \) follows trivially from Eq. (29a). In the next section, we provide solutions for this ansatz and a specific case of spin-bath coupling.

V. RESULTS

We are interested in the experimentally important case of a purely dephasing model, i.e., a bath coupled only via \( \sigma_z \) to the spin

\[
\tilde{A}(t) = A(t)\vec{\sigma}_z.
\]

Hence the coupling becomes simpler, but the bath dynamics itself is still kept in full generality. Spin flips do not occur in this model so that \( T_1 \) is infinite. But decoherence of the \( T_2 \) type is entirely kept. This assumption is justified in many experimental realizations. Moreover, the simplification of the coupling is advantageous for pulse shaping because it reduces the number of integral conditions derived from Eqs. (21b) and (22) in second order to be fulfilled from 39 to 3 first-order conditions and 6 second-order conditions which are given explicitly in Appendices A and B.

In the following, we present continuous pulses which fulfill the first-order conditions (first-order pulses) and pulses which fulfill all first- and second-order conditions (second-order pulses) for pure dephasing as in Eq. (32). Thereby, we provide optimized pulses that decouple the spin from the bath during the duration of the pulse up to \( O(t_p^2) \).

In order to consider a continuous frequency modulation we use the Fourier series ansatz

\[
\Phi(t) = \sum_n b_{2n-1} \sin(2\pi nt/\tau_p) + b_{2n} \cos(2\pi nt/\tau_p) - 1 \tag{33}
\]

for \( \Phi(t) \). We consider \( \pi \) and \( \pi/2 \) pulses because of their frequent use in QIP and NMR. Therefore, the pulse has to fulfill

\[
\psi(t_p) = \pi \quad \text{or} \quad \pi/2 \tag{34}
\]

for \( \pi \) pulses and \( \pi/2 \) pulses, respectively, according to Eq. (8). The value \( \theta(t_p) \) is fixed by the fact that the final axis of rotation has to be perpendicular to \( \sigma_z \) to rotate the spin by the full angle \( \psi(t_p) \). Thus we require

\[
\theta(t_p) = \frac{\pi}{2}. \tag{35}
\]

For a given ansatz, Eq. (33), the numerical procedure to find solutions is straightforward. We solve the differential equations (29) using a fourth-order Runge-Kutta algorithm. For this solution the conditions (21b), (22), (8), and (35) are evaluated. We search for roots using the Powell hybrid method in the GNU scientific library [40].

Of two different pulses the one with the lower amplitude \( V_0 \) is preferable in experiment because less power is needed to realize it. For an experimentally realizable maximum amplitude this implies that the theoretical pulse with lower amplitude can be made shorter, which is definitely advantageous.

<table>
<thead>
<tr>
<th>Table I. Overview of the pulses satisfying all first-order equations (21b). FM-1-PI denotes the frequency-modulated ( \pi ) pulse. FM-1-PI2 denotes the frequency-modulated ( \pi/2 ) pulse. The dimensionless coefficients ( b_n ) belong to the ansatz in Eq. (33). The amplitudes ( V_0 ) are given in units of ( 1/\tau_p ). With all eight digits given the conditions are fulfilled for the ( \pi ) pulse within ( 10^{-10} ) and for the ( \pi/2 ) pulse within ( 10^{-9} ). With only two digits they are fulfilled within ( 10^{-3} ) and ( 10^{-2} ), respectively.</th>
</tr>
</thead>
<tbody>
<tr>
<td>First-order pulses</td>
</tr>
<tr>
<td>FM-1-PI</td>
</tr>
<tr>
<td>----------</td>
</tr>
<tr>
<td>( V_0 )</td>
</tr>
<tr>
<td>( b_1 )</td>
</tr>
<tr>
<td>( b_2 )</td>
</tr>
<tr>
<td>( b_3 )</td>
</tr>
<tr>
<td>( b_4 )</td>
</tr>
</tbody>
</table>

FIG. 1. (Color online) First-order \( \pi \) pulse FM-1-PI. We also plot \( \sin \Phi(t) \propto v_1(t) \) and \( \cos \Phi(t) \propto v_2(t) \) to illustrate the pulse shape in spin space. The left scale refers to \( \Phi(t) \) and the right scale to \( \sin \Phi(t) \) and \( \cos \Phi(t) \), respectively. The Fourier coefficients for this pulse are given in Table I.

FIG. 2. (Color online) First-order \( \pi/2 \) pulse FM-1-PI2. We also plot \( \sin \Phi(t) \propto v_1(t) \) and \( \cos \Phi(t) \propto v_2(t) \) to illustrate the pulse shape in spin space. The left scale refers to \( \Phi(t) \) and the right scale to \( \sin \Phi(t) \) and \( \cos \Phi(t) \), respectively. The Fourier coefficients for this pulse are given in Table I.
TABLE II. Overview of the pulses satisfying all first- and second-order equations, Eqs. (21b) and (III). FM-2-PI and FM-2-PI2 denote the frequency-modulated π pulse and π/2 pulse, respectively. The dimensionless coefficients $b_\alpha$ belong to the ansatz in Eq. (33). The amplitudes $V_\alpha$ are given in units of $1/\tau_p$. With all eight digits given the conditions are fulfilled for the $\pi$ pulse within $10^{-10}$ and for the $\pi/2$ pulse within $10^{-11}$. With only two digits they are fulfilled within $10^{-2}$ and $10^{-2}$, respectively.

<table>
<thead>
<tr>
<th>$V_\alpha$</th>
<th>$b_1$</th>
<th>$b_2$</th>
<th>$b_3$</th>
<th>$b_4$</th>
<th>$b_5$</th>
<th>$b_6$</th>
<th>$b_7$</th>
<th>$b_8$</th>
<th>$b_{10}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>FM-2-PI</td>
<td>12.834 329 79</td>
<td>0.114 751 39</td>
<td>0.172 485 87</td>
<td>0.482 625 21</td>
<td>$-1.144 948 51$</td>
<td>$-0.208 790 91$</td>
<td>0.253 780 13</td>
<td>0.203 068 35</td>
<td>$-0.167 480 22$</td>
</tr>
<tr>
<td>FM-2-PI2</td>
<td>12.256 193 90</td>
<td>1.730 718 40</td>
<td>0.735 299 59</td>
<td>0.232 425 23</td>
<td>$-0.248 293 10$</td>
<td>$-0.071 022 04$</td>
<td>$-0.131 923 80$</td>
<td>1.079 482 26</td>
<td>0.122 200 06</td>
</tr>
</tbody>
</table>

Hence we search for pulses with lower amplitude among the second-order pulses. This is done by using an additional coefficient $b_9$ in the ansatz (33) and minimizing the amplitude $V_9$ of the resulting solutions by varying this additional coefficient.

A. First-order pulses

For first-order pulses and the pure dephasing model, the set of conditions (21b) comprises only three equations given in Appendix A. Adding conditions (34) and (35) five parameters are necessary to construct first-order pulses. One parameter is the amplitude $V_0$ and the others are the coefficients $b_\alpha$ in ansatz (33). The characteristics of the pulses are reported in Table I. The pulses are plotted in Figs. 1 and 2. Note that the composite and continuous amplitude-modulated pulses found in Ref. [30] have comparable amplitudes for first-order pulses.

FIG. 3. (Color online) Second-order $\pi$ pulse FM-2-PI. We also plot $\sin\Phi(t)$ and $\cos\Phi(t)$ to illustrate the pulse shape in spin space. The left scale refers to $\Phi(t)$ and the right scale to $\sin\Phi(t)$ and $\cos\Phi(t)$, respectively. The Fourier coefficients for this pulse are given in Table II.

FIG. 4. (Color online) Second-order $\pi/2$ pulse FM-2-PI2. We also plot $\sin\Phi(t) \propto v_1(t)$ and $\cos\Phi(t) \propto v_1(t)$ to illustrate the pulse shape in spin space. The left scale refers to $\Phi(t)$ and the right scale to $\sin\Phi(t)$ and $\cos\Phi(t)$, respectively. The Fourier coefficients for this pulse are given in Table II.

B. Second-order pulses

Second-order pulses additionally have to fulfill conditions (22). These equations again simplify for a purely dephasing bath leading to six additional integral conditions besides the first-order terms see Appendix B. Note that more equations are to be fulfilled than for amplitude modulation [30] because the frequency-modulated pulses involve all three spin directions. The solutions for $\pi$ and $\pi/2$ pulses are given in Table II and they are displayed in Figs. 3 and 4. Numerically, the double integrals in Eqs. B2 are particularly demanding. Full quantum mechanical studies of higher-order pulses will be hampered by even higher dimensional integrals occurring in the Magnus expansion [38]. An alternative route, which may be numerically more efficient, consists of the direct solution of the Schrödinger equation [24]. The mathematical existence of higher-order pulses is known [31].

Since we are interested in pulses with low amplitudes, we aim at minimizing the amplitude. To this end, we add another Fourier coefficient to the ansatz (33) and vary this additional parameter. In this way, we obtained the pulses FM-2-MIN-PI and FM-2-MIN-PI2 given in Table III and plotted in Figs. 5 and 6. Empirically it turned out to be more efficient to consider $b_{14}$ instead of $b_{11}$ as an additional coefficient. It is expected that even lower amplitudes can be achieved by using further coefficients. But our calculations with different coefficients, not shown here, indicate that this route would improve the amplitude only by 1%–2% at the expense of a more complex pulse shape.

By using only one free coefficient ($b_{14}$) we found $\pi/2$ pulses with amplitudes lower than $9.0/\tau_p$ to be compared with the amplitude-modulated pulses [30] with amplitude $11.5/\tau_p$. For $\pi$ pulses we need $V_0 = 10.7/\tau_p$ in comparison...
TABLE III. Overview of the pulses satisfying all first- and second-order equations, Eqs. (21b) and (22), with minimized amplitude. FM-2-PI and FM-2-P12 denote the frequency-modulated \( \pi \) pulse and \( \pi/2 \) pulse with minimized amplitude, respectively. The dimensionless coefficients \( b_{\nu} \) belong to the ansatz in Eq. (33). The amplitudes \( V_0 \) are given in units of \( 1/\tau_p \). With all eight digits given the conditions are fulfilled for the \( \pi \) pulse within \( 10^{-10} \) and for the \( \pi/2 \) pulse within \( 10^{-9} \). With only two digits they are fulfilled within \( 10^{-3} \) and \( 10^{-1} \), respectively.

<table>
<thead>
<tr>
<th>Minimized second-order pulses</th>
<th>FM-2-MIN-PI</th>
<th>FM-2-MIN-P12</th>
</tr>
</thead>
<tbody>
<tr>
<td>( V_0 )</td>
<td>10.707 114 54</td>
<td>8.435 414 12</td>
</tr>
<tr>
<td>( b_1 )</td>
<td>0.000 020 87</td>
<td>( b_1 )</td>
</tr>
<tr>
<td>( b_2 )</td>
<td>1.387 689 38</td>
<td>( b_2 )</td>
</tr>
<tr>
<td>( b_3 )</td>
<td>( -0.000 199 22 )</td>
<td>( b_3 )</td>
</tr>
<tr>
<td>( b_4 )</td>
<td>( -0.706 689 98 )</td>
<td>( b_4 )</td>
</tr>
<tr>
<td>( b_5 )</td>
<td>( -0.000 015 88 )</td>
<td>( b_5 )</td>
</tr>
<tr>
<td>( b_6 )</td>
<td>( 0.137 730 85 )</td>
<td>( b_6 )</td>
</tr>
<tr>
<td>( b_7 )</td>
<td>( 0.000 087 70 )</td>
<td>( b_7 )</td>
</tr>
<tr>
<td>( b_8 )</td>
<td>( 0.688 943 31 )</td>
<td>( b_8 )</td>
</tr>
<tr>
<td>( b_9 )</td>
<td>( -0.000 114 08 )</td>
<td>( b_9 )</td>
</tr>
<tr>
<td>( b_{10} )</td>
<td>( -0.697 440 86 )</td>
<td>( b_{10} )</td>
</tr>
<tr>
<td>( b_{14} )</td>
<td>( 0.465 019 91 )</td>
<td>( b_{14} )</td>
</tr>
</tbody>
</table>

FIG. 6. (Color online) Minimized second-order \( \pi/2 \) pulse FM-2-MIN-P12. We also plot \( \sin \Phi(t) \propto v_x(t) \) and \( \cos \Phi(t) \propto v_y(t) \) to illustrate the pulse shape in spin space. The left scale refers to \( \Phi(t) \) and the right scale to \( \sin \Phi(t) \) and \( \cos \Phi(t) \), respectively. The Fourier coefficients for this pulse are given in Table III.

VI. CONCLUSIONS

In this paper we extended the existing perturbative approach to decouple a spin from a quantum mechanical bath by means of short control pulses in two ways.

First, we allowed for a time-dependent bath, which means both the bath Hamilton operator and the coupling operators may have an explicit, analytical time dependence. Yet, we found that this time dependence does not alter the requirements for the pulse shape which were derived previously for time-independent baths \([30]\). Hence, the pulses found previously are also applicable for time-dependent environments as they arise, for instance, in time-dependent reference frames or in the interaction picture of otherwise time-independent Hamiltonians. This is our first key result.

Second, we studied frequency-modulated pulses in first order and in second order in the pulse duration \( \tau_p \) for quantum mechanical baths. Previously, only amplitude modulation was considered explicitly for quantum mechanical baths \([16, 27, 30]\). Frequency modulation was so far studied for static baths only \([23]\). We provide explicit solutions for continuous frequency-modulated pulses with amplitudes which have been minimized empirically. Such pulses are expected to be useful in experiments where no amplitude modulation can be realized or where the achievable accuracy for frequency modulation is superior to the accuracy of amplitude modulation. For instance, they can be used to implement realistic optimized dynamic decoupling \([33, 34]\) where the dynamic decoupling sequence is adapted to pulses of finite length. The frequency-modulated pulses constitute our second key result.

We emphasize that modulated pulses correspond to quantum gates which are robust against decoherence in the framework of quantum-information processing, e.g., the \( \pi/2 \) pulse about \( \sigma_z \), preceded by a \( \pi \) pulse about \( \sigma_x \), realizes the important Hadamard gate up to a global factor \( i \).

This fact was stated in Refs. \([28] \) and \([29]\) in a too shortened way, leaving out the \( \pi \) pulse.
Further work should concentrate on higher-order terms not studied here. Such terms comprise higher-dimensional integrals so that the numerical effort increases considerably. Another promising route is to extend the model from pure dephasing to general decoherence. This would allow for systems with finite $T_1$ as well, at the expense of more complex pulses.

But at the present stage, it is also called for to verify the performance of the proposed pulses experimentally in order to assess how promising further extensions would be.

ACKNOWLEDGMENTS

We thank Christopher Stihl, Nils Drescher, Frederic Keim, and Leonid Pryadko for useful discussions and comments. The study of frequency modulation was triggered by a discussion with Michael Biercuk and Hermann Uys. We acknowledge financial support of the DFG under Project UH 90/5-1.

APPENDIX A: FIRST-ORDER CONDITIONS

For the first-order conditions we inspect Eq. (21b) to find the corresponding scalar equations. In a purely dephasing bath the sum over $j$ collapses to $j = z$, resulting in the scalar equations

$$\eta_{11} = \int_0^{\tau} a_z(t) \sin[\psi(t)] - [1 - \cos(\psi)] a_y(t) a_z(t) dt, \quad (A1a)$$

$$\eta_{12} = \int_0^{\tau} a_z(t) \sin[\psi(t)] + [1 - \cos(\psi)] a_y(t) a_z(t) dt, \quad (A1b)$$

$$\eta_{13} = \int_0^{\tau} \cos[\psi(t)] + [1 - \cos(\psi)] a_z(t)^2 dt. \quad (A1c)$$

The $a_i$ are the components of the global axis of rotation parametrized in Eq. (28).

APPENDIX B: SECOND-ORDER CONDITIONS

For the second-order conditions, we additionally have to consider Eqs. (22) to find the corresponding scalar equations. Again certain sums collapse due to the purely dephasing bath model and we eventually obtain

$$\eta_{21} = \int_0^{\tau} [a_z(t) \sin[\psi(t)] - [1 - \cos(\psi)] a_y(t) a_z(t)] dt, \quad (B1a)$$

$$\eta_{22} = \int_0^{\tau} [a_z(t) \sin[\psi(t)] + [1 - \cos(\psi)] a_y(t) a_z(t)] dt, \quad (B1b)$$

$$\eta_{23} = \int_0^{\tau} [\cos[\psi(t)] + [1 - \cos(\psi)] a_z(t)^2] dt. \quad (B1c)$$

and

$$\eta_{24} = \int_0^{\tau} dt_1 \int_0^{\tau} dt_2 [n_{xz}(t_1) n_{yz}(t_2) - n_{xz}(t_1) n_{yz}(t_2)], \quad (B2a)$$

$$\eta_{25} = \int_0^{\tau} dt_1 \int_0^{\tau} dt_2 [n_{xz}(t_1) n_{yx}(t_2) - n_{xz}(t_1) n_{yx}(t_2)], \quad (B2b)$$

$$\eta_{26} = \int_0^{\tau} dt_1 \int_0^{\tau} dt_2 [n_{xz}(t_1) n_{yz}(t_2) - n_{xz}(t_1) n_{yz}(t_2)]. \quad (B2c)$$

The matrix elements $n_{ij}(t)$ occurring here are those of the rotation matrix $D_\theta(-\psi)$ given explicitly in Eq. (C1). The components $a_i$ are parametrized in Eq. (28).

APPENDIX C: ROTATION MATRIX

To derive the matrix $D_\theta(-\psi)$ we refer the reader to Ref. [30]. It is calculated by comparison of the coefficients in Eq. (17a). We obtain the matrix (C1) below, where the time dependencies of $\psi(t)$ and $\hat{a}(t)$ are omitted for clarity:

$$D_\theta(-\psi) = \begin{pmatrix}
\cos \psi + (1 - \cos \psi) a_z^2 & a_z \sin \psi + (1 - \cos \psi) a_x a_y & -a_z \sin \psi + (1 - \cos \psi) a_x a_y \\
a_z \sin \psi + (1 - \cos \psi) a_x a_y & \cos \psi + (1 - \cos \psi) a_y^2 & a_x \sin \psi + (1 - \cos \psi) a_y a_z \\
a_y \sin \psi + (1 - \cos \psi) a_x a_z & -a_x \sin \psi + (1 - \cos \psi) a_y a_z & \cos \psi + (1 - \cos \psi) a_z^2
\end{pmatrix}. \quad (C1)$$