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Detection of RF signal real-time phase based on spectral hole-burning material

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ABSTRACT

The detection of broadband signal power spectrum based on spectral hole-burning (SHB) material has been investigated a lot, but the detection of phase is not reported yet. In this paper, a method of RF signal real-time phase detection is proposed by applying the SHB material. Phase measurement is performed through the in-phase and in-quadrature components of emitted field generated by the macro polarization at steady state. The time range of reaching steady state is determined by numerical solution of Bloch equation solved by Runge–Kutta method. Furthermore, the effect of phase change rate on the accuracy of real-time phase measurement is also given. The typical RF signals are performed in the simulation to demonstrate the feasibility of the method and agreeable results are obtained in the phase value. Through the analysis of the effect of noise on the phase accuracy, When SNR is greater than 24 dB, phase error is less than 0.83%, and the phase error does not accumulate with time.

1. Introduction

Real-time RF signal phase detection, a frequently encountered task, occupies an important position in many applications, such as microwave measurements and chromatic dispersion measurement [1]. Until now, traditional electricity method also accounts for a large part in this field [2]. However, it is powerless for ultra wideband signal phase detection. Spectral hole-burning (SHB) material, as a spectrum analyzer, can handle signal bandwidth from a few gigahertzes to hundreds of gigahertz in experiments [3]. Nevertheless, it provides only power spectrum information of the signal field. As a consequence, many experiments do not provide as much information [4].

In the theoretical analysis on the phenomenon of hole burning which is the core problem of power spectrum detection, only the energy of corresponding frequency is considered, for which causes the inverse of the number of population *w*of Bloch component, that is, the effect of the amplitude not phase of the signal on the Bloch component [5,6]. Even in some Maxwell–Bloch numerical solution iterators [7,8], phase is also ignored. Only in the paper on the study of photon echoes, the signal phase is sometimes mentioned in Bloch equation [9–11]. Such as in Ref. [9], spatial phase was introduced in M–B equation to investigate effect of angled beam on photon echo, and linear frequency chirped as phase function was introduced

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in Bloch equation to programming the spatial-spectral grating in Ref. [10]. In fact, when input electric field incident into SHB material, the phase also causes the response of the atomic system and will be characterized by optical Bloch equation with phase which actually differs with traditional only by the contributions of certain anti-resonant terms [12].

In this paper, the main contents are as follows. Firstly, through the derivation of the Maxwell–Bloch transmission equation with phase, we find that signal phase can be measured by in-phase and in-quadrature of emitted generated by macro polarization under the steady state. Then, through the analysis of numerical solution of optical Bloch equation solved by Fourth-order Runge–Kutta iterator, time range of reaching steady state is determined approximately. Based on those analyses, the typical RF signals were performed in the simulation to demonstrate the feasibility of the method and agreeable results are obtained in the phase value. At the end of article, the influence of additive Gaussian noise on real time phase measurement is also analyzed.

2. Basic theoretical model

The Maxwell–Bloch equations that treat the medium quantum mechanically and treat field classically govern the evolution of the field and the atomic polarization and population components in an inhomogeneously broadened medium.

Starting with motion equation, the Bloch equation with phase term is derived. In two-level atoms, the motion equations can be written as [13]

$$\dot{\rho}_{21} = -i\hbar^{-1}\wp E(z,t)(\rho_{22}-\rho_{11}) - (i\omega_{21}+\gamma_{\perp})\rho_{21} \tag{1a}$$

$$\rho_{12} = \rho_{21}^{*} \tag{1b}$$

$$\dot{\rho}_{22}-\dot{\rho}_{11} = -\gamma_{\parallel}\left[(\rho_{22}-\rho_{11})-(\rho_{22}-\rho_{11})_0\right] + i\hbar\wp E(z,t)(\rho_{12}-\rho_{21}) \tag{1c}$$

where ρ_{21} represents microcosmic dipole moment, $\hbar$ is Plank constant, $\wp$ is the dipole matrix element of the transition, $E(z,t)$ denotes input signal field, '*' represents conjugate, ρ_{22},ρ_{11} denotes the number of atom of excited and ground state respectively, and $\rho_{22}-\rho_{11}$ is the population inverse, $(\rho_{22}-\rho_{11})_0$is equilibrium value of population inverse. $\omega_{21}=\omega_{12}$is atom's resonant frequency,$\gamma_{\perp}$, $\gamma_{\parallel}$ represent transverse relaxation term and longitudinal relaxation term respectively.

For Eq. (1a), in the absence of an external field, dipole moment will oscillates with the form of$\rho_{21} = \rho_{21}(0)\exp[-(i\omega_{21}+\gamma_{\perp})t]$. When input field is nonzero and is assumed propagating along the z-axis in space with the angular frequency $\omega$and the relative phase$\varphi(t)$that is a function of time $t$at $z=0$of the crystal, and can be written as

$$E(z,t) = \varepsilon(z,t)\cos(\omega t + \varphi(t)) \tag{2}$$

Such the dipole moment of atoms of corresponding frequency will oscillate as

$$\rho_{21} = \rho'_{21}\exp(-i\omega t) \tag{3}$$

where$\varepsilon(z,t)$,$\rho'_{21}$are slow-varying amplitude.

Then Eqs. (2) and (3) are substituted into the motion equation Eqs. (1a)–(1c), after the high order term is neglected, the following equation can be obtained,

$$\dot{\rho}'_{12} = -i(2\hbar)^{-1}\wp\varepsilon(z,t)(\cos(\varphi(t))+i\sin(\varphi(t)))(\rho_{22}-\rho_{11}) - (i(\omega_{12}-\omega)+\gamma_{\perp})\rho'_{12} \tag{4a}$$

$$\dot{\rho}'_{21} = i(2\hbar)^{-1}\wp\varepsilon(z,t)(\cos(\varphi(t))-i\sin(\varphi(t)))(\rho_{22}-\rho_{11}) + (i(\omega_{21}-\omega)-\gamma_{\perp})\rho'_{21} \tag{4b}$$

$$\dot{\rho}_{22}-\dot{\rho}_{11} = -\gamma_{\parallel}\left[(\rho_{22}-\rho_{11})-(\rho_{22}-\rho_{11})_0\right] + \frac{\wp\varepsilon(z,t)}{\hbar}\begin{bmatrix} i\cos(\varphi(t))(\rho'_{12}-\rho'_{21}) \\ +\sin(\varphi(t))(\rho'_{21}+\rho'_{12}) \end{bmatrix} \tag{4c}$$

Then Bloch vector $\mathbf{B}=[u,v,w]$ can be defined as [14]

$$u = \rho'_{12}+\rho'_{21} \tag{5a}$$

$$v = i(\rho'_{21}-\rho'_{12}) \tag{5b}$$

$$w = \rho_{22}-\rho_{11} \tag{5c}$$

Combining to Eqs. (4)and (5), Bloch equation with phase characterizing atom dynamics in the rotating frame can be expressed by

$$\dot{u} = -\Delta v - R\sin(\varphi(t))w - u/T_2 \tag{6a}$$

$$\dot{v} = \Delta u + R\cos(\varphi(t))w - v/T_2 \tag{6b}$$

$$\dot{w} = -R\left[v\cos(\varphi) - u\sin(\varphi(t))\right] - (w-w_0)/T_1 \tag{6c}$$

where$u$, v, $w$are in-phase, in-quadrature components and population inversion respectively, frequency detuning$\Delta=\omega_{12}-\omega$ is the difference between the atom's resonant frequency$\omega_{12}$and the laser frequency ω, Rabi frequency$R=\wp\hbar^{-1}\varepsilon(z,t)$, $T_2=1/\gamma_{\perp}$and$T_1=1/\gamma_{\parallel}$ are the coherent time and population lifetime. $w_0=-1$is the value of equilibrium. In two level atoms,