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Application of the low-finesse γ-ray frequency comb for high-resolution spectroscopy

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High-finesse frequency combs (HFC) with large ratio of the frequency spacing to the width of the spectral components have demonstrated remarkable results in many applications such as precision spectroscopy and metrology. We found that low-finesse frequency combs having very small ratio of the frequency spacing to the width of the spectral components are more sensitive to the exact resonance with absorber than HFC. Our method is based on time domain measurements reviling oscillations of the radiation intensity after passing through an optically thick absorber. Fourier analysis of the oscillations allows to reconstruct the spectral content of the comb. If the central component of the incident comb is in exact resonance with the single line absorber, the contribution of the first sideband frequency to oscillations is exactly zero. We demonstrated this technique with γ-photon absorption by Mössbauer nuclei providing the spectral resolution beyond the natural broadening.

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I. INTRODUCTION

Techniques using femtosecond-laser frequency combs allow to measure extremely narrow optical resonances with high resolution [1–4]. This is achieved by comparison of one of the spectral components of the calibrated frequency comb with the frequency of an extremely stable laser, which is tuned in resonance with the narrow absorption line under investigation. Broadband high-resolution x-ray frequency combs were proposed to be generated by the x-ray pulse shaping method, which imprints a comb on the excited transition with a high photon energy by the optical-frequency comb laser driving the transition between the metastable and excited states [5,6]. Enabling this technique in the x-ray domain is expected to result in wide-range applications, such as more precise tests of astrophysical models, quantum electrodynamics, and the variability of fundamental constants.

Special kind of γ-ray frequency combs were generated much earlier by Doppler modulation of the radiation frequency, induced by mechanical vibrations of the source or a resonant absorber [7–15] . They were observed in the frequency domain and appear only if the source and the absorber were used in a couple. Contrary to the optical and x-ray combs, discussed above, γ-ray frequency combs do not produce sharp, short pulses in time domain, except in the cases where some additional conditions are satisfied [16,17].

These special γ-ray frequency combs with high finesse $F \gg 1$, where F is the ratio of the comb-tooth spacing to the tooth width, demonstrated that in many cases determination of small energy shifts between the source and absorber can be made more accurately in the time domain by transient and high-frequency modulation techniques than by conventional methods in frequency domain [12,13,18]. In time-domain-spectroscopy technique, the γ-ray frequency comb is transmitted through a single line absorber whose resonant transition is studied. Out of resonance the phase modulation of the field, generating the frequency comb, does not produce the modulation of the field intensity at the exit of the absorber. If one of the comb components comes to resonance with the absorber, the intensity of the transmitted radiation acquires oscillations. Their pattern is very sensitive to the resonant detuning.

We have to emphasize that in γ domain even standard spectroscopic measurements with such a popular Mössbauer isotopes as ^{57}Fe and ^{67}Zn have already demonstrated extremely high-frequency resolution in measurements of gravitational redshift [19–21]. This is because the quality factor Q, which is the ratio of the resonance frequency to the linewidth, is very high for these nuclei. For example, the 14.4-keV transition in ^{57}Fe has $Q = 3 \times 10^{12}$ and the 93.3-keV resonance in ^{67}Zn demonstrates $Q = 1.8 \times 10^{15}$. Appropriate sources emitting resonant or very close to resonance γ photons with high Q are available for both nuclei. They are ^{57}Co for ^{57}Fe and ^{67}Ga for ^{67}Zn. Here we show that a low-finesse comb (LFC) with $F \ll 1$ is more sensitive to the small resonant detuning between the fundamental of the radiation field and the absorber compared with the high-finesse comb (HFC).

II. FREQUENCY COMBS IN γ DOMAIN: FREQUENCY AND TIME DOMAIN MEASUREMENTS

The basic idea of the modulation technique in γ domain is that the pistonlike vibration of an absorber leads to a periodic modulation of the resonant nuclear transition frequency with respect to the frequency of the incident photons owing to the Doppler effect. This modulation induces coherent Raman scattering of the incident radiation in the forward direction transforming a quasimonochromatic field into a frequency comb at the exit of the absorber [15]. The relative amplitudes and phases of the produced spectral components are defined by the vibration amplitude d and frequency Ω, the detuning of the central frequency of the radiation source ω_S from the resonant frequency of the absorber ω_A, the linewidths of the source Γ_S and absorber Γ_A, and the absorber optical depth T_A.

To describe the transformation of the quasimonochromatic radiation field into a frequency comb, it is convenient to consider the interaction of the field with nuclei in the reference frame rigidly bounded to the pistonlike vibrated absorber. There, nuclei "see" the quasi-monochromatic source radiation with the main frequency ω_S as polychromatic radiation with a