Spectral flux enhancement of X-rays via coherent control of Mossbauer nuclei

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Novel short-wavelength radiation sources such as x-ray free-electron lasers open the possibilities to control nuclear transitions with light and extend quantum coherent effects from the optical to X-ray range. Coherent manipulation of nuclear transitions is hindered by low spectral fluxes of X-ray sources, radiating pulses with spectral bandwidths orders of magnitude wider than the nuclear resonances, at most providing one resonant X-ray photon per pulse. The most advanced X-ray source to date - the recently opened European XFEL, has a spectral flux of \(\sim 10^{-4}\) photons/Hz/pulse at energies < 30 keV, and the more advanced self-seeded XFELs are expected to produce \(\sim 10^{-2}\) photons/Hz/pulse. This will give > 10\(^2\) resonant photons for the most popular Mossbauer \(^{57}\)Fe nucleus having the transition with the width of 1.1 MHz (excited state lifetime 141 ns), but for nuclei with transition widths smaller than 10 kHz still about one photon per pulse will be resonant. Nuclear transitions with narrow linewidths < Hz will increase the precision of Mossbauer spectroscopy and can potentially be used for nuclear clocks expected to surpass current atomic clocks in accuracy and stability. We propose an approach to enhance the spectral intensity of X-ray radiation in a desired narrow frequency range by sending it through a resonant Mossbauer absorber. The spectral flux enhancement can be realized by placing the absorber in a longitudinal (along the incident field propagation direction) magnetic field gradient, which produces a spatial gradient of the transition frequency of Mossbauer nuclei. The part of the incident field spectrum within the gradient width, which can be significantly larger than the width of the Mossbauer nuclei transition, will be absorbed and stored as a nuclear excitation. By reversing the sign of the frequency gradient at a later time the stored excitation can be converted back into radiation and re-emitted by the nuclear ensemble, similar to gradient echo memory technique. The spectral width and intensity of the re-emitted field can be manipulated by tuning the magnitude of the reversed gradient. In particular, the width can be made of the order of the Mossbauer resonance one, and the maximal spectral flux at nuclear resonance can significantly exceed the intensity of the incident field. The spectrally enhanced X-ray field can be used to probe nuclear transitions such as a potential nuclear clock transition of \(^{45}\)Sc.