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Intelligent Quantum Sensing with Computational Neuromorphic Imaging

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Abstract: This work presents a solution that leverages the synergy of diamond quantum sensing and computational neuromorphic imaging, which brings high precision and a significant computation time reduction. It gives impetus to the advancement of more intelligent quantum sensing and computing capacity.

1. Introduction

Solid-state quantum sensors have revolutionized the approaches to detection by offering exceptional sensitivity in the measurement of magnetic, electric fields, and temperature [1]. Among the various platforms explored, the Nitrogen Vacancy (NV) center is one of the most promising options. Such an optically addressable defect in diamond possesses remarkable electronic spin features, particularly at the indoor temperature. Typically, the optically detected magnetic resonance (ODMR) technique detects the electron spin state, sweeping the microwave frequency while monitoring the fluorescence intensity over time in parallel. Therefore, we harness ODMR measurements for quantum sensing based on NV centers in diamonds. As Fig. 1(a) depicts, excited with a green laser, the spin states of NV centers can be observed via the emitted red fluorescence, since there is a transition between the ground and excited states of the triplets. Conventional diamond quantum sensing exploits frame cameras to record a sequence of frames of NV fluorescence at a fixed rate, with consistent efforts towards enhancing measurement accuracy and spatial resolution. An illustration is shown in Fig. 1(b). However, frame imaging is a kind of synchronous acquisition of all pixels within the field of view. Accordingly, it also captures redundant background fluorescence outside regions of interest (ROI), as Fig. 1(c) shows. This results in a relatively low frame rate, hindering high-speed dynamic ODMR measurements.

Bio-inspired computational neuromorphic imaging (CNI) mimics the neural architecture of the human retina to perceive brightness variations of scenes and generates asynchronous streaming events on a frame-free basis in response [2, 3]. Such a novel imaging modality enjoys microsecond-level temporal precision ($\sim$ 10 µs) as well as a high dynamic range ($\sim$ 120 dB), and consequently it has strong robustness to an environment with frequent changes and extreme illumination. Therefore, CNI is standing under the spotlight for a number of emerging applications, such as fast-autofocusing [4], fast-localization [5], and wavefront sensing [6]. Diamond quantum sensing fits close with the outstanding features of CNI, since the rapid yet rare spatiotemporal variations in fluorescence intensity typically occur near the resonance frequency, resulting in the sparse nature of the data. In this work, we explore their synergy via a diamond quantum sensing approach based on neuromorphic vision sensors.

2. Methodology

Fig. 1(d) presents that a neuromorphic vision sensor encodes the variation of fluorescence intensity into an event (or spike) stream, where an event is triggered once the change, which occurs significantly near the resonance, exceeds a threshold value. Events are exclusively generated within the ROI in which there exist intensity changes, bringing highly compressed data volume and achieving considerably reduced delay in transmission and processing. With each event being denoted in a spike-like function $\mathbf{e}_i(t) = p_i\delta(t-t_i)$, where p_i and t_i are the polarity and timestamp of an event indexed by i respectively, the (logarithmic) fluorescence intensity $\mathbf{I}(t)$ over a time t can be estimated by integrating a stream of events $\mathbf{I}(t) = \int_0^t \sum_i p_i\delta(\tau - t_i)\,\mathrm{d}\tau$, and the approximated change for a short time Δt is

$$\Delta\mathbf{I}(t) \approx \frac{\partial}{\partial t}\mathbf{I}(t)\Delta t. \tag{1}$$

Fig. 2 shows ODRM measurements under frame imaging and CNI, respectively. Conventionally, we fit the frame intensity that changes in response to microwave frequency with a Lorentzian function to observe the resonance frequency (*i.e.*, f_0). Alternatively, when employing CNI, f_0 can be obtained by fitting with the derivative Lorentzian spectrum estimated based on the accumulation of events triggered over a specific time period.

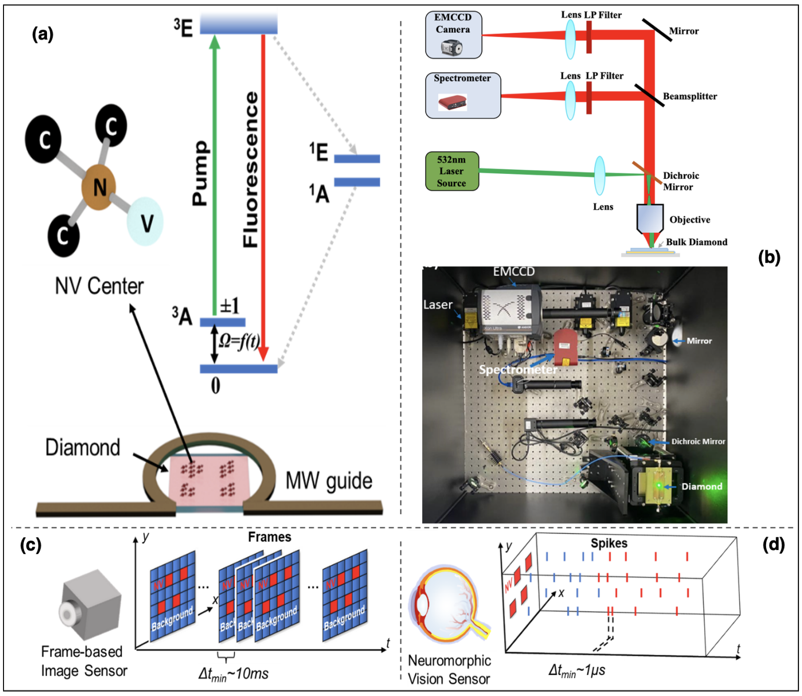

Fig. 1. Illustration of frame- and event-based diamond quantum sensing. (a) Principle of NV center based quantum sensing. (b) Experimental setup for a frame-based implementation. (c) Frames recorded by a frame camera. (d) Events (spikes) produced by a neuromorphic vision sensor.

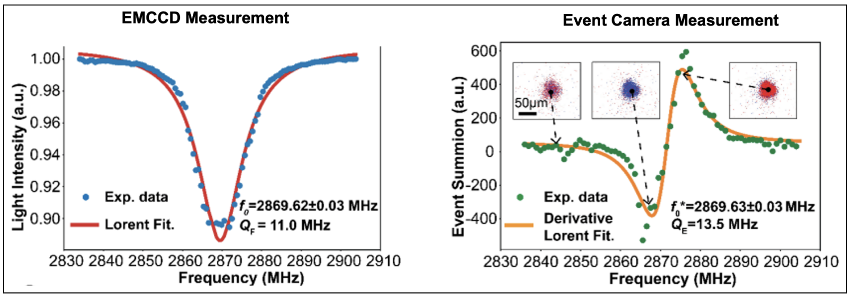

Fig. 2. ODMR measurements under frame imaging (left) and CNI (right).

3. Conclusion

This work presents the use of neuromorphic vision sensors on diamond quantum sensing. Such a synergy brings much more efficient measurements and processing.

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