Camera-based modal fingerprinting of cavity resonances in a photonic crystal nanobeam

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Abstract: Utilizing distinct features in the leaky region of k-space as ‘modal fingerprints’, we demonstrate resonant mode identification in a photonic crystal nanobeam via infrared camera measurements with a ~19dB detection SNR improvement over transmission measurements.
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1. Introduction

Photonic devices enable many optical applications in the nano-scale via engineered control of optical fields in space and time. As optical confinement enables strong interactions between light and matter, many nanophotonic devices are designed with metrics such as temporal confinement (given by quality factor, Q), spatial confinement (given by mode volume, Vm) and modal shape in mind to improve control of optical fields and advance device performance [1,2]. As Q, Vm and mode shape vary highly between supported modes, it is crucial in many applications to be able to identify and distinguish between different modes in nanophotonic devices. Typically, this is done by analyzing mode-related spectral features in the frequency domain or through near-field measurements of optical power in the spatial domain [1,2]. While features in the frequency domain, such as resonance peaks or pass bands, are easily measurable, they can be subject to positional shifts or suppression from coupling configuration or fabrication variation, which can lead to mode misidentification. Spatial field profiles are often more robust identifiers of mode order, but they are often harder to measure, as they require probing in the near-field [1]. This work aims to show it is possible to simultaneously gain robust and easily attainable modal information for nanophotonic devices by probing modal features which exist in k-space. By using unique modal features that exist in the leaky region of k-space as a ‘modal fingerprint’, it is possible to distinguish between optical modes by measuring scattering which propagates into the far-field. To demonstrate this concept, we show mode identification and improved resonance detection for modes in a photonic crystal nanobeam (PCN) cavity using an infrared (IR) camera.

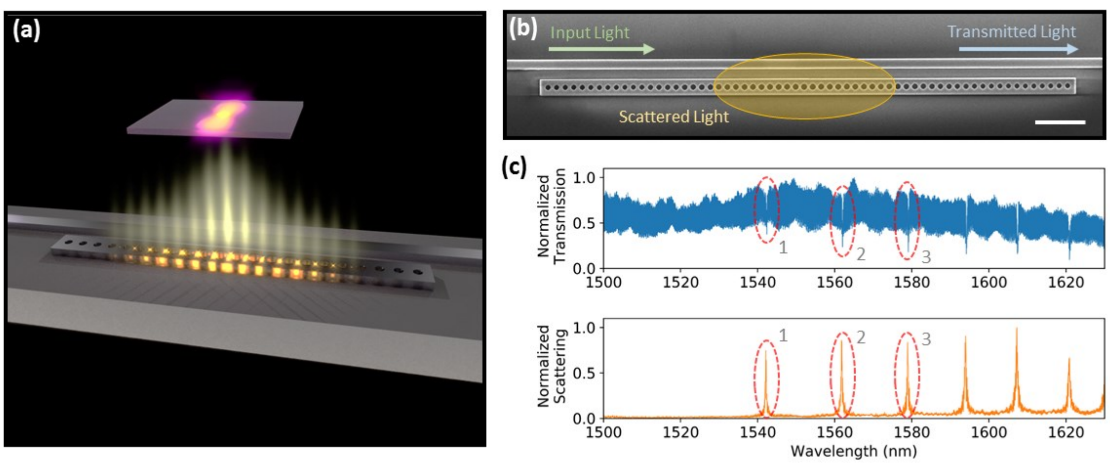

Figure 1: (a) Illustration of measurement concept. Excitation of the PCN resonance mode leads to scattering. The pattern of scattering (dependent on the mode shape in the leaky region) is detected by a camera in the far-field. (b) SEM of measured device showing device operation. White scale bar is 2um. (c) Transmission (top) and scattering (bottom) measurements from the PCN cavity, showing improved SNR in scattering measurements. The first three resonant mode orders are labeled (1), (2) and (3) for first order, second order and third order, respectively.

2. Method and Results

To demonstrate modal fingerprinting of optical resonances, we designed and fabricated PCN cavities using standard techniques [3]. As shown in Fig. 1(a,b), a side-coupled configuration was used to excite PCN resonances and the resonant scattering from the cavity was detected using a camera. The transmission through the bus waveguide and scattering intensity were both measured to compare resonance signal-to-noise ratio (SNR). It can be seen in Fig. 1(c) that the SNR of resonance measurement is dramatically improved in scattering measurements and the SNR of the fundamental resonance (labeled 1) is improved by ~19dB, leading to more reliable resonance detection.

To explore how resonant scattering may be used to identify mode order, we simulated PCN cavity modes using FDTD simulations. Figure 2(a) illustrates the spatial field profiles of the first three resonant modes in the designed PCN cavity (also indicated 1, 2 and 3 in Fig. 2(c)). It is clearly seen that these field profiles have distinct characteristics in the spatial domain. By taking the Fourier transform of these profiles, it is possible to observe the mode profiles in k-space. Figure 2(b) shows that in k-space, the PCN cavity modes have unique features which lie within the leaky region (circled in black). Because k-vectors in the leaky region are supported in free space, scattering simulations of these modes (Fig 2(c)) show the unique patterns in the leaky region are directly translated into the far-field. Measured scattering from fabricated PCN devices in Fig. 2(d) shows camera detection of these scattering profiles to enable the experimental identification of resonance modes. The robustness of this measurement to peak shifts in frequency space is demonstrated in our recent journal paper [3].

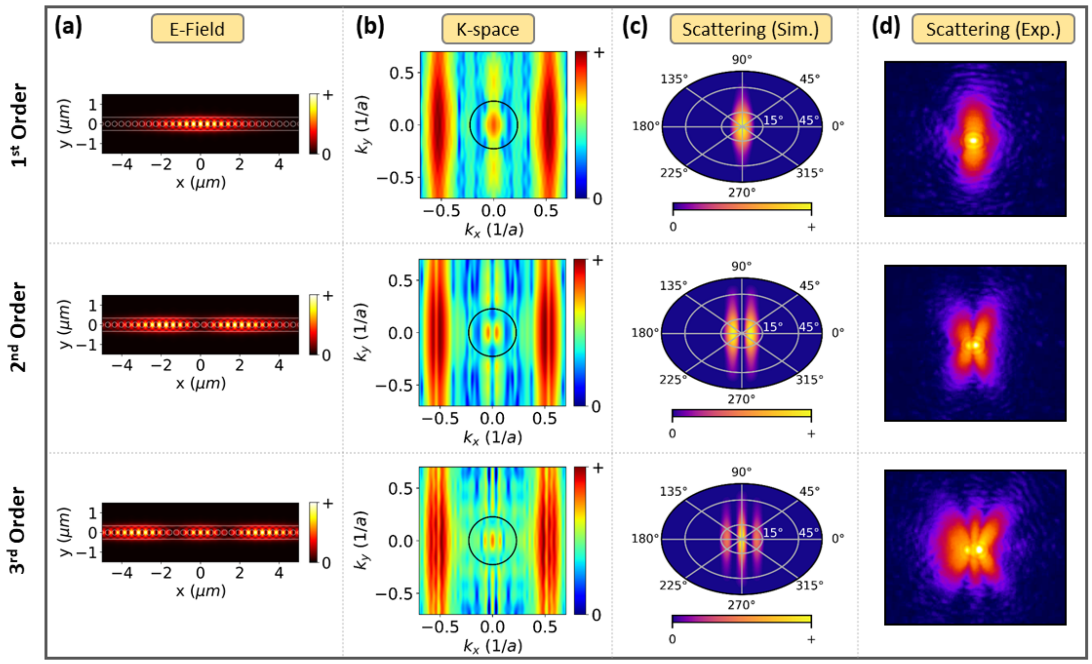

Figure 2: Comparison of first three resonance modes in the PCN cavity. These three modes are also indicated in the spectra in Fig 1(c). (a) Electric field profile for the resonance modes. (b) Fourier transform of electric field to show k-space profile of modes. (c) Calculated modal scattering. (d) measured modal scattering profiles for the scattering measurement in Fig 1(c).

3. Conclusions

As the properties of nanophotonic devices and their utility to optical applications hinge on their supported optical modes, it is vitally important to detect and distinguish between modes. While modal features in the frequency domain are easy to measure, they can show high variability which may lead to mode misidentification. In contrast, modal features in the spatial domain are more robust, but often require more difficult measurement in the near-field. Through implementing an IR camera to detect resonant scattering, we demonstrate improved resonance detection (~19dB increase in SNR) and mode order identification of optical modes in a photonic crystal nanobeam. This work opens the door to utilizing modal fingerprints in k-space to quickly and reliably characterize nanophotonic modes and furthers investigation of the leaky region for predicting and potential engineering of mode-dependent optical scattering.

4. References

[1] S. Hu, M. Khater, R. Salas-Montiel, E. Kratschmer, S. Engelmann, W. M. J. Green, and S. M. Weiss, "Experimental realization of deep subwavelength confinement in dielectric optical resonators," *Sci. Adv.* **4**, eaat2355 (2018).

[2] Q. Quan, P. B. Deotare, and M. Loncar, "Photonic crystal nanobeam cavity strongly coupled to the feeding waveguide," *Appl. Phys. Lett*. **96**, 203102 (2010).

[3] F. O. Afzal, J. M. Petrin and S. M. Weiss, "Camera detection and modal fingerprinting of photonic crystal nanobeam resonances," *Opt. Express* **27**, 14623 (2019)

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