Supplementary information for

On-chip optical vector analysis based on thin-film lithium niobate single-sideband modulators

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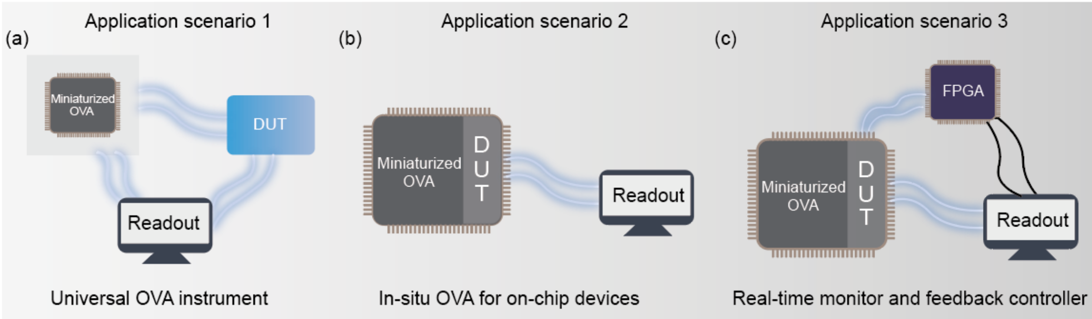
Supplementary Note I: Different application scenarios



Supplementary Fig. S1 Different application scenarios of our proposed OVA system. (a) A miniaturized OVA instrument. (b) As an in-situ OVA for integrated photonic devices. (c) As a real-time monitor and dynamic control of photonic networks

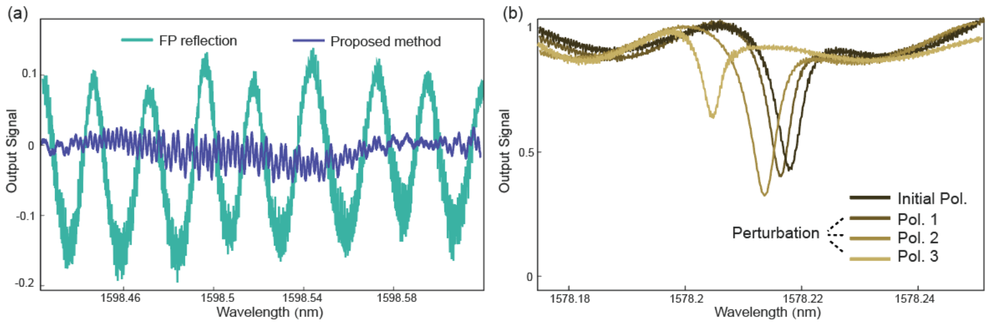
We envision three different application scenarios that our on-chip OVA system can contribute to, which are schematically illustrated in Supplementary Fig. S1:

Application scenario 1: A miniaturized OVA instrument. First of all, our proposed on-chip OVA, which integrates an LN phase modulator and a flat-top filter, can operate in the same manner as traditional SSB-based OVA systems, where the DUTs are physically separated from the OVA system [Fig. S1(a)]. Compared with bulk modulator-based OVAs, our proposed system features significantly improved size, weight, and power consumption (SWaP) performances. This instrument miniaturization opens up new possibilities for high-resolution real-time monitoring in mobile and remote devices, such as underwater and satellite operations.

Application scenario 2: In-situ OVA for integrated photonic devices. Building on the first application scenario (a miniaturized instrument), we then envision a second application scenario, where the DUT could be placed on the same chip as our integrated OVA, enabling in-situ OVA that could be beneficial for certain applications. Leveraging the excellent scalability of our LN platform, the in-situ OVA mode provides unambiguous information extraction of DUTs with minimal influence from environmental fluctuations and peripheral interconnecting components [Fig. S1(b)]. Such delicate measurement capability could be crucial for the accurate characterization and fine-tuning of novel and complex photonic devices and circuits, such as the synthetic frequency crystal demonstrated in the main text. Moreover, a comprehensive statistical analysis of the fabrication tolerance can be implemented through multiple iterative OVA measurements. This will provide a deeper understanding of the reliability in the photonic circuit design and help devise strategies to mitigate the effects of fabrication variations. Furthermore, given the excellent tunability and scalability of the LN platform, EO/TO switches can also be incorporated between a single SSB modulator and different on-chip DUTs, allowing for in-situ measurements of multiple DUTs using a single on-chip OVA device.

Application scenario 3: Real-time monitoring and dynamic control of photonic networks. Our in-situ OVA can be further combined with electronic chips to achieve real-time monitoring and feedback control of complex photonic circuits [Fig. S1(c)]. For example, the coupling states and resonant wavelengths of a microring resonator network could easily drift over time due to environmental fluctuations. The amplitude and phase responses of the complex network could be monitored in real-time using our in-situ OVA and fed into a pre-trained electronic chip (such as FPGA) to generate the corresponding tuning signals and apply them to the on-chip tuning elements (such as heaters). Moreover, the wavelength (de-)multiplexers can be employed before and after the DUTs to separate wavelength bands for functional operation and real-time monitoring, while avoiding the extra tap loss in the monitoring system. Alternatively, an optical switch could be inserted to switch the optical power to either the OVA measurement port or the functional port. A short measurement could be performed periodically to keep the system at the correct operation point over long time, while at other time the system operates normally without power loss or interference from the OVA. Therefore, such an in-situ feedback system could play an important role in maintaining the stable operation of complex photonic networks like large-scale optical neural networks.

Supplementary Note II: Advantages of in-situ measurement



Supplementary Fig. S2 (a) Measurement backgrounds in ex-situ measurement with obvious Fabry-Perot fringes caused by facet reflections (green) and our proposed in-situ method (blue). (b) Measured optical transmissions of a microring resonator at different input polarization perturbation states.

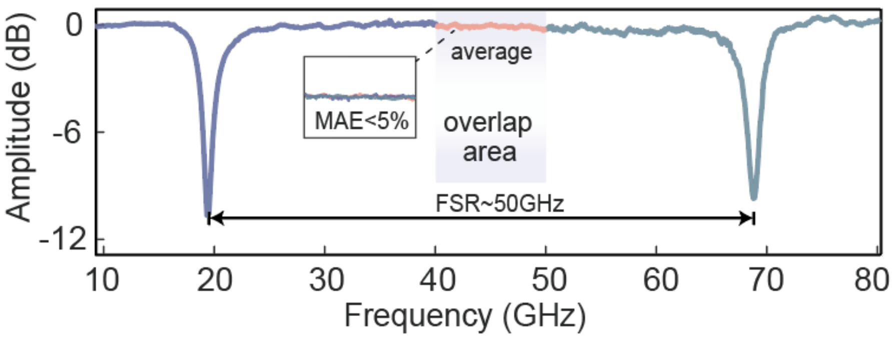
As shown in Supplementary Fig. S2, the advantages of our in-situ measurement are as follows. First, the undesired Fabry-Perot interference caused by coupling facet reflection can be effectively suppressed, leading to more accurate and stable measurements of amplitude and phase information. Second, our method allows for effective and flexible control of polarization perturbations caused by environmental fluctuation, significantly reducing the complexity of the overall system. To further illustrate the benefits of our system, we have carried out additional experiments:

1. Fabry-Perot interference. The undesired Fabry-Perot interference caused by coupling facet reflection, especially in the probe of on-chip DUTs, often introduces additional undesired amplitude and phase features [green line in Fig. S2 (a)], resulting in substantial uncertainties in the measurement results. On the contract, due to the DUTs being in the same chip as the OVA system, the Fabry-Perot interference can be effectively suppressed in in-situ measurements, leading to a smoother and more stable background with better measurement accuracy [blue line in Fig. S2(a)].

2. Polarization perturbation. In ex-situ measurements, the responses of DUTs could be substantially affected by the input polarization states. For example, when we perturb the location and orientations of input optical fibers, the measured optical transmission spectrum of

a microring resonator could be substantially changed [Fig. S2(b)]. As the extinction ratios of the resonance notches fluctuate under different perturbations, we expect the corresponding phase response would also vary accordingly, thereby introducing test uncertainties. In our method, the input optical polarization is controlled by monitoring the spectral characteristics of the flat-top filter, which in turn ensures a deterministic polarization control of the DUTs since they are directly connected to the OVA on the same chip. This effectively reduces measurement errors caused by polarization perturbation of input optical fibers.

Supplementary Note III: Post-process of the stitching process



Supplementary Fig. S3 Post-process of stitching process using single microring resonator as an example. The average value is adopted in the overlap area when the mean absolute error of the two consecutive measurements < 5%

Supplementary Fig. S3 illustrates an example of the stitching post-process between two consecutive measurements. Considering a microring resonator with FSR ~ 50 GHz as an example, the first reliable measurement bandwidth ranges from 10 GHz to 50 GHz (blue line), where a resonance peak is observed at 19 GHz. The second reliable measurement bandwidth spans from 40 GHz to 80 GHz (green line), capturing another resonance peak around 69 GHz. The overlapping region between 40 GHz and 50 GHz is analyzed by first comparing the mean absolute error (MAE) between the two measurements. If the error exceeds 5%, both datasets will be remeasured. Conversely, if the error is less than 5%, the average of the two measurements will be considered as the value for the overlapping region to ensure continuity (red line).