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Cite as: APL Photonics 3, 036101 (2018); https://doi.org/10.1063/1.5000108
Submitted: 14 August 2017. Accepted: 29 January 2018. Published Online: 05 March 2018

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Highly localized distributed Brillouin scattering response in a photonic integrated circuit

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(Received 14 August 2017; accepted 29 January 2018; published online 5 March 2018)

The interaction of optical and acoustic waves via stimulated Brillouin scattering (SBS) has recently reached on-chip platforms, which has opened new fields of applications ranging from integrated microwave photonics and on-chip narrow-linewidth lasers, to phonon-based optical delay and signal processing schemes. Since SBS is an effect that scales exponentially with interaction length, on-chip implementation on a short length scale is challenging, requiring carefully designed waveguides with optimized opto-acoustic overlap. In this work, we use the principle of Brillouin optical correlation domain analysis to locally measure the SBS spectrum with high spatial resolution of 800 µm and perform a distributed measurement of the Brillouin spectrum along a spiral waveguide in a photonic integrated circuit. This approach gives access to local opto-acoustic properties of the waveguides, including the Brillouin frequency shift and linewidth, essential information for the further development of high quality photonic-phononic waveguides for SBS applications. © 2018 Author(s).

I. INTRODUCTION

Stimulated Brillouin scattering (SBS) is an opto-acoustic interaction, in which the energy of the pump wave transfers into a frequency down-shifted probe wave (Stokes) through an acoustic wave. SBS enables many applications such as narrow linewidth lasers, optical delay lines, temperature and strain sensors, microwave generation, and signal processing. In particular, the possibility to generate SBS on-chip opens a new paradigm for compact integrated devices in a small footprint. Harnessing SBS on-chip, however, is challenging since SBS scales exponentially with the interaction length. To achieve strong opto-acoustic coupling, it is necessary to confine the optical and acoustic mode simultaneously in a small cross section. One possibility is to use soft-glass waveguides sandwiched between a more rigid cladding material, however, in recent years more complex structures were put forward to generate strong on-chip opto-acoustic overlap, such as under-etched silicon waveguides, hybrid silicon-silicon nitride membranes, fully suspended nanowires, bandgap-engineered soft-glass waveguides, or multi-material hybrid circuits. The high complexity of the waveguides that guide optical and acoustic waves and the sensitivity of these modes to even small variations in geometry requires a technique to probe the opto-acoustic coupling strength on a sub-millimeter length scale. These new insights will help to better understand local

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https://doi.org/10.1063/1.5000108
parameters effecting the overall SBS gain response, ensuring high performance and high yield of the photonic waveguides. In addition, as part of the design process, it is critical to study and characterise new designs against the simulation results and understand the effect of local design parameters such as tapers, bends, and couplers on the overall opto-acoustic response of the waveguide.

Numerous distributed SBS measurement techniques have been developed, including Brillouin optical time domain analysis (BOTDA),\textsuperscript{13,32,33} Brillouin echo distributed sensing (BEDS),\textsuperscript{34,35} and Brillouin optical correlation domain analysis (BOCDA).\textsuperscript{12,36,37} BOTDA has limited spatial resolution since the pump pulses should not be shorter than the phonon lifetime (corresponding to 1 m spatial resolution in an optical fiber). The BEDS proposal was put forward to overcome this limitation relying on a short $\pi$ phase shift applied to the continuous wave (CW) pump instead of a pulsed pump, which improves the spatial resolution down to 1 cm.\textsuperscript{13,34} BOCDA enables millimeter order spatial resolution through broad spectrum pump and probe whose product in the time domain is a spatially localized correlation peak. The linewidth of this correlation peak defines the spatial resolution of the system.

The first BOCDA technique was based on the broad-spectrum frequency-modulated pump and probe waves.\textsuperscript{36,38} A more advanced setup using the same technique was introduced in Ref. 11, where 3 mm spatial resolution in a fiber was experimentally demonstrated. Also, a 5.9 mm spatial resolution Brillouin frequency shift measurement in planar lightwave circuit (PLC) was reported in Ref. 39. Following the initial demonstration of BOCDA, different variations of BOCDA have been introduced, including a random bit phase-modulated pump and probe,\textsuperscript{40} Golomb-code modulated pump and probe,\textsuperscript{41} and noise-based correlation technique.\textsuperscript{42,43} The realization of the broad-spectrum pump and probe through the frequency and phase modulation adds to the complexity of the experiment and limits the measurement range due to multiple correlation peaks, whereas the noise-based correlation technique relies only on the amplified spontaneous emission (ASE) of an erbium-doped fiber,\textsuperscript{32} which offers simplicity and high spatial resolution. 3 mm spatial resolution and 4 mm spatial resolution in fiber were reported in Refs. 44 and 42, respectively, using the noise-based approach. However, the noise-based approach suffers from a limited signal-to-noise ratio (SNR) mainly due to the stochastic nature of the ASE source.

In this work, we chose the latter approach to characterise chalcogenide photonic waveguides since this technique offers the highest spatial resolution based on a simple ASE source. We demonstrate a record on-chip spatial resolution using this noise-based BOCDA measurement, and a significant improvement in the SNR is achieved by adding a lock-in amplifier (LIA) to the setup. We spatially resolve the Brillouin response of a chalcogenide photonic waveguide on a chip with a high spatial resolution of 800 $\mu$m, which we believe is the smallest section over which SBS has been observed in a planar waveguide. This setup employs the ASE of an erbium-doped fiber to resolve features such as the waveguide thickness and the resultant effective refractive index change of an As$_2$S$_3$ photonic waveguide. This work provides the basis for the understanding of a very local interaction of optical and acoustic waves and the design of novel waveguide structures.

II. PRINCIPLE OF OPERATION

SBS is an inelastic scattering effect, in which two counter-propagating optical pump and probe waves generate a moving index grating in the medium, which travels with the acoustic velocity ($v_a$). The pump wave is back-scattered by the moving index grating, which results in a frequency down-shifted Stokes wave in the backward direction. The frequency difference between the pump and the Stokes is called the Brillouin frequency shift (BFS) $\Omega_B$ and is defined as\textsuperscript{22,45}

$$\Omega_B = \frac{2n_{\text{eff}}v_a}{\lambda},$$

where $n_{\text{eff}}$ is the effective refractive index of the medium and $\lambda$ is the pump wavelength. The BFS depends upon the optical material as well as the waveguide dimensions and environmental conditions such as temperature and strain, which makes SBS suitable for sensing purposes.\textsuperscript{9,12,37} In order to employ SBS as a distributed sensing approach, a localize BFS measurement is required. Among the different distributed SBS techniques introduced in Sec. I, we select BOCDA since it provides the highest spatial resolution down to mm-scale,\textsuperscript{11,42} which is the preferred method for mapping cm-scale integrated photonic circuits.\textsuperscript{30}
The key to realize a localized SBS measurement using BOCDA is that unlike the conventional SBS measurement technique, which relies on the coherent pump and probe signals, BOCDA employs a highly non-coherent signal as the pump and the probe. In general, the cross-correlation function between the pump and the probe signals (could also be called the auto-correlation function since the pump and the probe signals are driven from the same source) defines the spatial resolution of the local SBS response. For an integrated SBS measurement, the coherent pump and probe signals create a constant cross-correlation function along the medium; therefore, the SBS response is the accumulative gain collected from the entire length of the medium. In BOCDA, however, the cross-correlation between the non-coherent pump and probe signals gives rise to a spatially localized correlation peak, which confines the SBS response into a narrow region and suppresses it elsewhere in the medium. This gives access to a localized SBS response and is illustrated in Fig. 1(a).

A filtered ASE source with a bandwidth of 80 GHz and its auto-correlation function are shown in Figs. 1(b) and 1(c), respectively. The bandwidth $\Delta f$ of the ASE spectrum defines its coherence time $\Delta t$ by $\Delta t \Delta f \approx 1$. Therefore, the spatial resolution of the localized response can be adjusted by changing the ASE bandwidth.

The overall SBS gain $g$ is obtained by adding together the individual local Brillouin gain spectrum $g_B$, spatially weighted by the cross-correlation function over the entire length of the waveguide using the following equation:

$$g = \frac{\nu_e P_1}{A_{\text{eff}} \Delta t} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} g_B(\tau, \nu) |\chi(\tau, \nu)|^2 d\nu,$$

where $\nu_e$ is the group velocity of light in the medium, $P_1$ is the average pump power, $A_{\text{eff}}$ is the waveguide effective area, and $\chi(\tau, \nu)$ is a two-dimensional function, which defines the cross-correlation between the complex envelope of the pump $u(t)$ and the probe $u(t-\tau)$ as a function of the delay ($\tau$) and the frequency shift ($\nu$) between the pump and the probe. $\chi(\tau, \nu)$ is calculated using the following equation:

$$\chi(\tau, \nu) = \frac{n c \varepsilon_0 A_{\text{eff}}}{2 \sqrt{P_1 P_2}} \int_{-\infty}^{\infty} u(t) u^*(t-\tau) \exp(i2\pi\nu t) dt,$$

where $n$ is the refractive index of the medium, $c$ is the speed of light in the vacuum, $\varepsilon_0$ is the free space permittivity, and $P_2$ is the average probe power. Equation (3) is also known as the ambiguity function since it introduces a degree of ambiguity in the measured Brillouin gain spectrum. A simulation of the ambiguity function for the 80 GHz ASE spectrum pump and probe is shown in Fig. 1(d).

![FIG. 1. (a) Correlation peak in the waveguide as a result of broad-spectrum pump and probe. (b) 80 GHz ASE spectrum and (c) its auto-correlation function in a dB scale along the waveguide. (d) Ambiguity function of an 80 GHz square ASE spectrum in a $\text{As}_2\text{S}_3$ waveguide, the colormap is scaled with the normalized linear power of the ambiguity function.](image-url)
In this simulation, the medium is a 17.5 cm chalcogenide waveguide with the BFS of 7.6 GHz, and the pump and the probe arms are assumed to have the same length (zero delay between the pump and the probe). The delay between the pump and the probe can be translated into the position in the waveguide using the relation \( x = \frac{1}{2}(v_g \tau + L) \), where \( v_g \) is the group velocity in the waveguide and \( L \) is the total length of the waveguide. As it can be seen in Fig. 1(d), the correlation peak occurs in the middle of the waveguide (plotted in a linear scale), and the frequency response is maximum at 7.6 GHz.

In our experiments, a filtered ASE of an erbium-doped fiber is used as the common source for the pump and the probe. The correlation peak position is moved along the medium using a delay line to change the relative delay between the pump and the probe arms. The integral sum of the local Brillouin gain spectrum multiplied by the local spectrum of the ambiguity function over the length of the medium is measured for each delay step, which is referred to as the local SBS response in this document. This product is maximum at the correlation peak and is suppressed by the shape of the correlation function at any other point. The contribution of these points adds to the ambiguity (noise) of the overall Brillouin gain spectrum.

III. EXPERIMENT AND DISCUSSION

A. Experimental setup

The experimental setup is shown in Fig. 2(a). The ASE spectrum of an erbium-doped fiber passes through a polarization beam splitter (PBS) and is filtered to a square-shape spectrum. The bandwidth of the band-pass filter varies from 25 GHz to 89 GHz depending on the desired spatial resolution. An erbium-doped fiber amplifier (EDFA) is used to pre-amplify the polarized filtered ASE, which is then divided between the pump and the probe arms with a power ratio of 30%–70%, respectively.

The pump signal is modulated by a Mach-Zehnder modulator (MZM) using square pulses of 500 ns width and 5% duty cycle. The same radio-frequency (RF) source that drives the MZM triggers the lock-in amplifier (LIA) with the reference frequency of 100 kHz. In the probe arm, a dual-parallel Mach-Zehnder modulator (DPMZM) is used to generate a single sideband (SSB), down-shifted by the BFS (10.8 GHz for SMF and approximately 7.6 GHz for chalcogenide waveguides). This technique results in 25 dB of sideband and carrier suppression, which is critical to improve the SNR. The SSB is swept over a 350 MHz frequency span around the BFS using an automated RF signal generator to measure the SBS gain spectrum. The delay line is swept automatically to change the delay between the pump and the probe arms, thus changing the position of the correlation peak in the medium. The pump and the probe signals counter-propagate through the medium, and the back-scattered signal (Stokes) is collected at port 3 of the circulator. At the LIA, only frequency components which match the frequency of the pump pulses (reference frequency) are detected and amplified, and the rest of the amplified noise is filtered out by the BPF.
the ASE spectrum coming from the probe is rejected; this will improve the SNR of the measurement. Also, since SBS is a polarization sensitive process and our waveguide is strongly birefringent, careful consideration was taken during the measurement to align the polarization of the pump and the probe signals to the fundamental TE mode. Once the polarization is optimised, it remained unchanged during the measurement.

B. Signal-to-noise ratio (SNR)

The SNR for this experiment is defined as the ratio of the increment in the expected value of the detector reading due to the SBS amplification ($\Delta W$) to the detector noise ($\sigma_W$) as described in Ref. 42,

$$\text{SNR} = \frac{\Delta W}{\sigma_W}. \quad (4)$$

After substituting the terms $\Delta W$ and $\sigma_W$ from Ref. 44, the SNR can be summarized as follows:

$$\text{SNR} = \frac{g_B P_P}{A_{\text{eff}}} \sqrt{\frac{\nu_g T \Delta x}{2}}, \quad (5)$$

where $g_B$ is the SBS gain coefficient, $P_P$ is the peak pump power, $A_{\text{eff}}$ is the effective waveguide area, $\nu_g$ is the group velocity, $T$ is the LIA integration time, and $\Delta x$ is the spatial resolution. In our devices, $g_B/A_{\text{eff}}$ is in the order of 400 mW$^{-1}$, the detector integration time is 50 ms, and depending on the peak pump power and the spatial resolution of the measurement, the SNR varies from 36 dB to 38 dB. It should be noted that we calculated the SNR by taking into account the contribution from the LIA, which is not present in the previously reported measurement, where instead a large number of averaging was performed to improve the signal detection.

The SNR of this measurement is mainly limited by the stochastic nature of the ASE source. In addition, since this measurement is carried out in a photonic waveguide, we have a strong back reflection component at the reference frequency (100 kHz) due to the waveguide facets and Rayleigh back scattering. The contribution of the pump back-reflection is therefore always present in the measurement and deteriorates the experimental SNR.

C. Scanning the waveguide

We aim to fully detect and resolve a short As$_2$S$_3$ rib waveguide. The waveguide is 2.2 $\mu$m wide with a slab thickness of 600 nm and a ridge thickness of 330 nm as shown in Fig. 2(b). The light is coupled into and out of the waveguide using lensed fibers with an approximate coupling loss of 4.2 $\pm$ 0.2 dB per facet. The propagation loss is about 0.2 dB cm$^{-1}$, and the total loss of the waveguide is 9 $\pm$ 0.5 dB at the pump peak power of 27 dBm.

The filter bandwidth is set to 25 GHz corresponding to the 2.5 mm spatial resolution in the waveguide according to

$$\Delta x \approx \frac{1}{2} \nu_g \Delta t, \quad (6)$$

where $\nu_g = \frac{c}{n_g}$ and $n_g$ is the group index of the waveguide.

The delay line and the RF signal generator are controlled by a computer program; the delay line takes 1 mm steps at every 5 s, and the RF signal generator sweeps the probe signal over 350 MHz span with 2.5 MHz spectral resolution for each delay step. For every frequency, the back-scattered signal is collected at port 3 of the circulator and is measured by the LIA.

By moving the correlation peak through the waveguide using the delay line, a map of local Brillouin responses is created as shown in Fig. 3(a). The region over which the local Brillouin responses are detected is approximately 20.8 mm, corresponding to the length of the waveguide.

By fitting the local responses with a Lorentzian profile, a map of BFS over the length of the waveguide is established. The BFS over this region is fairly consistent with a mean value of 7.58 GHz and a standard deviation of 3.2 MHz, which confirms the uniformity of the waveguide. In order to confirm this measurement, the waveguide is scanned in a reverse direction; that is, the pump and the probe directions are swapped. This measurement also shows a consistent BFS over the waveguide length. The BFS associated with the two measurements is shown in Fig. 3(b).
A local Brillouin response at a random position in the waveguide (1.4 cm from the waveguide input facet) is shown in Fig. 3(c). A Lorentzian profile is fitted to the measured points, which has a linewidth of 41 MHz and a maximum at 7.58 GHz, corresponding to the linewidth and the BFS of the local SBS gain spectrum. The measured local gain at this position is approximately 0.15 dB, and the SNR according to Eq. (4) is 25 dB. The discrepancy between the calculated and the measured SNR is mainly due to the strong pump back-reflection coming from the waveguide facets.

The filter bandwidth is then increased to 80 GHz, which corresponds to a spatial resolution of 800 µm in the waveguide. The edge of the waveguide is resolved using this high spatial resolution setting as it is shown in Fig. 3(d). Since the SBS interaction length is only 800 µm, an averaging over four measurements is required to resolve this region. The delay steps in the delay line are set to 1 mm in free space, and the scanning range is over 3 mm length of the waveguide. As the correlation peak travels from the lensed fiber into the chalcogenide waveguide, the optical field experiences different effective refractive indexes. This means that for a fixed delay step in free space (1 mm), the delay steps outside the waveguide are longer (0.33 mm) than the delay steps inside the waveguide (0.2 mm). This feature can be seen in Fig. 3(d).

D. Waveguide characterization

The second experiment aims to look at the uniformity of a long spiral waveguide (17.5 cm long), which consists of several 180° bends (with a bend radius of approximately 200 µm) as well as straight regions. The waveguide is in the form of a rib waveguide and is 2.4 µm wide with a slab thickness of 600 nm and a ridge thickness of 330 nm.

The filter bandwidth is set to 62.5 GHz, corresponding to 1 mm spatial resolution in the waveguide. The waveguide insertion loss is 15 ± 1 dB, and the pump peak power before coupling is set to 29 dBm. The spectral resolution of the measurement is 2.5 MHz, and each local measurement takes 5 s to complete. Figure 4(a) shows a map of local Brillouin responses over the first 5 cm of the waveguide, which is closer to the pump arm. As it is plotted in Fig. 4(a), the local BFS gradually changes in an oscillating pattern as we scan through the waveguide. In order to confirm this measurement, the waveguide is scanned in the reverse direction by physically swapping the pump and the probe connections to the waveguide. As it is shown in Fig. 4(b), which is a mirrored image of the first scan, the same variations in the local BFS are observed when the direction of the scan is changed. From Fig. 4(b), it can be seen that the SNR of the local responses in the second scan is lower compared to the first scan. This is due to the fact that the two measurements are not symmetric. In the first measurement, we scan the edge of the waveguide (toward the pump), whereas in the second measurement, the pump and probe are swapped and the pump is now located further away from the scanning region. Therefore, the pump signal experiences an additional propagation loss (3.5 dB), which results in a lower SNR.

Figure 4(c) confirms that the local BFS in the forward and the reverse scan matches. In addition, a local BFS variation of 22 MHz is observed in this plot. This suggests that the optical mode experiences
varying effective refractive index as it propagates through the waveguide, according to Eq. (1). By matching the BFS to the waveguide layout, as shown in Fig. 4(d), it can be seen that as we scan from the edge of the waveguide toward the bends and travels back to the edge, the BFS changes accordingly. This confirms that the waveguide has a lower effective refractive index at the edge and slightly higher effective refractive index at the center. The linewidth of the local SBS responses along the waveguide is shown in Fig. 4(e). The standard deviation is 1.53 MHz and 6.03 MHz for the forward and the backward scan, respectively. The local Brillouin response and its Lorentzian fit at position 2 cm from the edge of the waveguide for the forward measurement are depicted in Fig. 4(f). The local gain at this position is measured to be 0.9 dB, and the SNR according to Eq. (4) is 26.7 dB.

**E. Simulation and analysis**

In order to confirm the effective refractive index variation, we used the spectroscopic reflectometry technique to obtain the refractive index information of the chalcogenide film across the wafer with a resolution of 1 cm². Figure 5(a) shows the reflectometry result where the red box indicates the region which is scanned by the BOCDA setup. The map indicates 0.008 index variation over 20 mm length of the waveguide. In addition, we investigate the effect of deposition and etching non-uniformity on the effective refractive index by sweeping the ridge and the slab thicknesses over the fabrication variation of ±5% using a commercial-grade simulator eigenmode solver and propagator.

![FIG. 4. BOCDA scan of the long waveguide in the (a) forward direction and (b) reverse direction (the colormap shows the normalized power in a linear scale). (c) BFS of the forward and the backward scan. (d) The mask layout and the schematic of the scanned region in the waveguide. (e) Local SBS linewidth of the forward and reverse scan. (f) Local SBS response at position 2 cm from the front facet in the forward direction.](image)

![FIG. 5. (a) Refractive index map of the wafer taken by a spectroscopic reflectometer (the BOCDA scanned region is indicated by the red box). (b) Simulation result of variation in the BFS as a function of slab thickness and waveguide thickness.](image)
FIG. 6. (a) Scan of a 1 mm piece of DSF spliced in between the SMF fiber with 1.1 mm spatial resolution (the colormap shows the linear normalized power). (b) Local SBS response at different positions of the sample.

The result is presented in Fig. 5(b). From this figure, a change of 22.8 MHz in the BFS occurs if the ridge and the slab thicknesses increase by 5% from the edge of the waveguide toward the center, which agrees well with the BOCDA measurement. It should be mentioned that this photonic chip, which has extreme variation in its refractive index values (not a typical one), was selected to enable us to track these changes with our BOCDA system.

The effect of the bends on the effective refractive index change and consequently the BFS change is also studied; the numerical simulation indicates the 3 MHz BFS change due to the bends for the fundamental TE mode (which is the dominant mode in the waveguide) and 120 MHz change in the BFS as a result of coupling to the higher order mode. Comparing these values with the experimental observation confirms that the BFS variation is not due to the bends and that the optical mode remains unaffected by the bends.

F. Spatial resolution confirmation

In order to confirm the spatial resolution of the BOCDA setup, detection of a 1 mm long dispersion shifted fiber (DSF) spliced in between the two pieces of a single mode fiber (SMF) with a slightly different BFS is demonstrated.

The ASE bandwidth is set to 89 GHz, which corresponds to 1.1 mm spatial resolution in a silica fiber. The correlation peak is moved by 0.2 mm steps in a fiber. As it moves from the SMF into the DSF and back to the SMF again, the BFS of the local Brillouin responses changes from 10.89 GHz to 10.68 GHz and back to 10.89 GHz, as shown in Fig. 6(a). Figure 6(b) shows the appearance and disappearance of the DSF peak over the short region of 1 mm. As it is observed in Fig. 6(b), the SMF peak is present in all the traces since part of the correlation peak always overlaps with the SMF. However, the amplitude of the SMF peak is the lowest when the correlation peak is entirely inside the DSF and has minimum overlap with the SMF. The SNR in this measurement is low because the silica fiber has a lower SBS gain compared to the As$_2$S$_3$ waveguide. Therefore, we averaged the measurement over four traces to fully recover the DSF piece.

IV. CONCLUSION

A BOCDA distributed SBS measurement with an on-chip spatial resolution of 800 $\mu$m and 1.1 mm spatial resolution on the fiber is presented. This sub-mm spatial resolution is achieved despite the challenges present in the photonic waveguide measurement including sensitive power handling, strong polarization sensitivity, additional loss due to the coupling from the fiber to the waveguide, and strong back-reflection due to the waveguide facets, which are not present in any of the fiber-based measurements previously reported. The issue of SNR reported in Ref. 42 was addressed using a LIA detection technique. Using this setup, we demonstrate the degree of uniformity of the As$_2$S$_3$ waveguide. As a proof of principle demonstration, we resolved 5% variations in the waveguide thickness, which is in agreement with expected fabrication tolerances. This demonstration presents the first on-chip SBS response measurement with sub-mm resolution and opens up new opportunities to discover fundamental opto-acoustic effects locally in SBS integrated platforms, which have not yet been studied closely. In addition, from the design optimization point of view, this setup will enable
us to study the local SBS response in any part of the waveguide which is sensitive to the geometrical variations such as tapers and bend regions in long spiral waveguides, which is critical for designing new opto-acoustic waveguides.

ACKNOWLEDGMENTS

The authors would like to thank Mr. Blair Morrison and Dr. David Marpaung for their insightful discussions during this work.

This work was funded by Australian Research Council (ARC) Centre of Excellence CUDOS (CE110001018) and ARC Laureate Fellowship (FL120100029). We acknowledge the support of the ANFF ACT and a joint grant from the Max Planck Society and the Fraunhofer Society (PowerQuart).

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