Interpolarization Forward Stimulated Brillouin Scattering in Standard Single-Mode Fibers

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Forward stimulated Brillouin scattering in standard single-mode fibers draws increasing interest toward sensing and signal processing applications. The process takes place through two classes of guided acoustic modes: purely radial ones and torsional-radial modes with twofold azimuthal symmetry. The latter case cannot be described in terms of scalar models alone. In this work, the polarization attributes of forward stimulated Brillouin scattering in single-mode fibers are investigated in analysis and experiment. Torsional-radial acoustic modes are stimulated by orthogonally polarized pump tones, a first such report in standard single-mode fibers. The scattering of optical probe waves by torsional-radial modes may take up the form of phase modulation, cross-polarization coupling, or a combination of both, depending on polarization. Lastly, this analysis predicts that circular and orthogonal pump tones may stimulate acoustic vortex beams: torsional-radial modes that are rotating. The rotation represents the transfer of angular momentum between the polarization degree of freedom of the light field and the acoustic wave.

1. Introduction

Forward stimulated Brillouin scattering (forward SBS) is an opto-mechanical nonlinear interaction between two copropagating optical field components and a guided acoustic wave in a common medium.[1–4] The guided acoustic waves may be driven through two continuous optical waves, pulsed modulation of coherent sources and even modulated amplified spontaneous emission noise. The process has been studied extensively in standard optical fibers,[1–3,5] photonic-crystal and nanostructured fibers,[6–9] and photonic integrated circuits.[10–13] Applications of forward SBS include narrowband laser sources,[13] soliton lasers,[6,9] and microwave-photonic signal processing.[14,15] Interest in forward SBS over standard fibers has reawakened in recent years due to the prospects of sensing and analysis of media beyond the fiber cladding, where light does not reach.[16–19]

Forward SBS processes in standard, single-mode fibers (SMFs) take place through two discrete sets of guided acoustic modes:[1–4] radially symmetric modes (denoted by $R_{0,m}$ where $m$ is an integer) and torsional-radial modes with twofold azimuthal symmetry (TR$_{2,m}$ modes). Both classes of modes may be stimulated by a pair of copropagating optical field components (pump waves), with proper detuning between their frequencies.[1–4] Once generated, the acoustic waves may scatter and modulate additional optical probe fields.[1–4]

Many characteristics of forward SBS in SMF are well accounted for by scalar analysis.[20] For example, the stimulation of purely radial acoustic modes requires that the two pump waves are copolarized,[1–4] and the stimulation process is independent of the specific state of polarization of the pumps.[1–4] Moreover, the scattering of probe waves by radial acoustic modes is independent of the specific polarization of the probe as well and does not affect the probe polarization.[1–4] On the other hand, forward SBS processes involving torsional-radial modes mandate vector treatment. In the first publication on the subject, Shelby et al. already addressed the polarization coupling of probe waves due to scattering by TR$_{2,m}$ modes.[1] This property, which has been used in few recent demonstrations of optical fiber sensors based on forward SBS,[21] cannot be described by scalar models. However, the study of the polarization properties of forward SBS in SMF has not been complete. Vector theories of opto-mechanical interactions, previously employed to more complex fiber and waveguide geometries,[6,22,23] carry additional, nontrivial implications on the important specific case of forward SBS processes in SMF. These implications are related to the stimulation of the torsional-radial modes by pump tones of different polarizations, as well as the scattering of optical probe waves by the same acoustic modes. They were not pointed out or experimentally demonstrated in the initial work of Shelby et al. or in other previous studies.[1–4]

In this work we provide a comprehensive analytic and experimental study of the polarization properties of forward SBS in standard SMFs through torsional-radial modes. We show that unlike radial modes, TR$_{2,m}$ acoustic modes may be stimulated...
by optical pump waves with linear states of polarizations that are either aligned or orthogonal. The possibility of forward SBS through orthogonally polarized pump tones has been studied in specialty fibers,\cite{6} and was recently investigated in polarization maintaining fibers as well.\cite{24} However, this option was not yet considered in standard SMFs.

The material displacement profiles of TR\textsubscript{2m} modes are characterized by two orthogonal principal axes.\cite{1–4} We show that the orientation of the principal axes depends on the pump waves. When linearly polarized pumps are coaligned, one principal axis of acoustic displacement takes up the same direction as well. By contrast, if the two linearly polarized pumps are orthogonal to each other, the principal axes of displacement are rotated by 45° with respect to the optical polarizations. Further, we find that the scattering of probe light by TR\textsubscript{2m} modes depends on its state of polarization with respect to the principal axes. Linearly polarized probe waves aligned with either axis are phase modulated by the guided acoustic waves. On the other hand, probe waves polarized with equal-magnitude projections on the two principal axes undergo cross-polarization coupling to the orthogonal state instead.

Special consideration is given to pump waves of circular polarizations. Our analysis suggests that pumps with coaligned circular polarization cannot stimulate TR\textsubscript{2m} guided acoustic modes. Pump waves of opposite circular polarizations, on the other hand, may give rise to acoustic vortex beams:\cite{25–30} torsional-radial modes with rotating principal axes. The stimulation of acoustic vortex beams represents the transfer of angular momentum between the polarization degree of freedom of the optical field and the acoustic wave.\cite{25–30} Acoustic vortex beams were previously studied based on external, mechanical excitations, however their Brillouin stimulation has yet to be considered. The optical stimulation of the acoustic vortex beams mandates complete degeneracy between two azimuthal orientations of a torsional-radial acoustic mode, and it is therefore possible in SMF. It is not supported in complex fiber or waveguide geometries that are not radially symmetric.

The formalism extends the understanding of forward SBS in standard fibers. The results constitute a first report of stimulating guided acoustic waves in standard SMF through orthogonally polarized pumps, in either forward or backward directions. The polarization properties allow for the selective excitation of torsional-radial modes only, and selective scattering by the same modes, with potential applications in fiber sensors. Rotating acoustic waves, in particular, may be used to couple between optical modes with different angular momenta.\cite{25–32}

2. Experimental Section

2.1. Sagnac Interferometer Loop Measurements

The experimental setup for the characterization of forward SBS processes in a Sagnac interferometer loop is presented in Figure 1.\cite{16,33,34} Light from a first laser diode at 1550 nm wavelength was modulated into short and isolated pump pulses of 1 ns duration and 5 μs period using an electro-optic amplitude modulator. The broadband pulses excited a packet of multiple
acoustic modes. The pump pulses were amplified by an erbium-doped fiber amplifier (EDFA) to 100 mW average power and launched into a section of fiber under test that was embedded in a Sagnac interferometer loop. Pump pulses were coupled into the fiber in the clockwise direction only and were blocked from reaching the loop output by a tunable optical bandpass filter. In some experiments a polarization controller was used to adjust the pump pulses polarization for maximum stimulation of torsional-radial guided acoustic modes (see Section 3). In other measurements, a polarization scrambler was used instead in order to eliminate the contribution of the same modes from the ensemble average of repeating acquisitions. The temporal shape of the pump pulses $P(t)$ was recorded, and its Fourier transform $\tilde{P}(\Omega)$ was calculated offline and used in data analysis (see below). The standard SMF under test was 30 m long, and it was stripped of its protective polymer coating to obtain stronger acoustic stimulation.

A continuous probe wave from a second laser diode source at 1532 nm wavelength was coupled into the loop in both directions. The tunable optical bandpass filter inside the loop was aligned to transmit the probe wavelength. Forward SBS induced phase modulation $\Delta \phi(t)$ to the clockwise-propagating probe wave. For the fiber length and the pump power levels used, $\Delta \phi(t) \ll 2\pi$. Due to the wavenumber matching characteristics of the process, the counter-clockwise propagating probe wave was largely unaffected. The nonreciprocal phase modulation due to acoustic waves was converted to intensity modulation of the probe wave at the Sagnac loop output. The output probe wave was detected by a photoreceiver of responsivity $R = 27 \text{ V} \times \text{W}^{-1}$ and 15 ps rise time. Polarization controllers were used to adjust the bias value of the non-reciprocal phase difference between the two directions of propagation of the probe wave. Given proper bias adjustments, the detected voltage $V(t)$ is simply related to the forward SBS phase modulation: $V(t) \approx RP_0[1 + \Delta \phi(t)]$. Here $P_0 = 2$ mW is the probe power at the loop output with the pump pulses turned off. The detector output voltage was sampled using a real-time digitizing oscilloscope, averaged over 4096 repeating acquisitions and processed further offline.

In addition to forward SBS, the probe wave also undergoes cross-phase modulation by the pump pulses via the Kerr effect. However, the contribution of the instantaneous Kerr effect vanishes as soon as the pump pulse ends, whereas phase modulation through forward SBS continues for hundreds of nanoseconds or longer. Time gating of collected $V(t)$ traces removes the Kerr effect from the analysis of phase modulation. The normalized forward SBS spectrum of the fiber under test is estimated using the radio-frequency power spectrum $\left| \tilde{V}(\Omega) \right|^2$ of the gated traces

$$\left| V(\Omega) \right|^2 \propto \left| \tilde{V}(\Omega) \right|^2 / \left| \tilde{P}(\Omega) \right|^2.$$  

2.2. Measurements of Optical Power Coupling between Pump Waves

The coupling of power between two orthogonal pump tones due to forward SBS was measured using the setup illustrated in Figure 1b. Light from a laser diode at 1530 nm wavelength was split into two paths. The optical wave in one branch was upshifted by a fixed intermediate frequency offset $\Omega_{IF}$ of $2\pi \times 10$ GHz using a single-sideband electro-optic modulator. A sine wave of radio frequency $f_s = 2\pi \times 40 \text{ kHz}$ from one output port of a dual lock-in amplifier was superimposed on the modulating waveform using an electro-optic amplitude modulator. Light in the first branch was then amplified by an EDFA to 500 mW power. The laser output in the second branch was upshifted by a variable frequency $\Omega_p + \Omega$ using another single-sideband electro-optic modulator, amplitude modulated by a sine wave of frequency $f_s = 2\pi \times 50 \text{ kHz}$ from a second output port of the same lock-in amplifier in another electro-optic amplitude modulator, and amplified in a second EDFA to 500 mW power.

The two pump waves were connected to the two input ports of a polarization beam combiner. The device transmits $x$ (y) polarized light only from input port 1 (2) to the common output. Manual polarization controllers were used to align both pump waves for maximum transmission to the polarization beam combiner output. The combined tones were therefore of linear and orthogonal polarizations. The pump waves were then launched into a bare, 6 m long section of SMF under test. The fiber length was shorter than typical beat lengths of residual birefringence in SMF, hence polarization rotations remained small. A polarization beam splitter at the output end of the fiber routed a single pump wave component to a photoreceiver and rejected the other. The properties of the receiver were the same as above. The detected voltage was analyzed by the lock-in amplifier input. Coupling of optical power between the two tones due to forward SBS was identified through oscillations of the detected voltage at the sum radio frequency $f_s + f_j$. The coupling scales with the imaginary part of the inter-modal forward SBS coefficient: $2\text{Im}(\gamma(\Omega))$ (see Section 3).

2.3. Measurements of Phase Modulation and Cross-Polarization Scattering of Probe Waves

The setup for measuring the scattering of probe waves by torsional-radial guided acoustic modes is shown in Figure 1c. Light from a first laser diode at 1544 nm wavelength was modulated into short and isolated pump pulses of 1 ns duration and 5 $\mu$s period using an electro-optic amplitude modulator. The pump pulses were amplified by an EDFA to 500 mW average power and launched into a 30 m long section of bare fiber under test. The state of polarization of the pump pulses at the fiber under test input was adjusted by a manual polarization controller. A tunable optical bandpass filter blocked the pump pulses at the output of the fiber under test.

A continuous probe wave from a second laser diode source at 1550 nm wavelength was coupled into the fiber under test along-side the pump pulses. The input probe power was 50 mW. The input state of polarization of the probe wave was adjusted by a second polarization controller. The tunable optical bandpass filter at the fiber under test output was aligned to transmit the probe wavelength. Phase modulation and cross-polarization coupling of the probe wave were monitored in parallel by two detection channels. In one analysis branch, the probe wave passed through a fiber Bragg grating with maximum reflectivity of 90% at 1530 nm wavelength and a spectral full width at half maximum of 0.04 nm. The exact wavelength of the probe wave was adjusted.
to a maximum slope of the grating spectrum using temperature and current tuning of the laser diode source. Reflection from the grating converted phase modulation of the probe wave to an intensity signal.

Light at the grating output was detected by a photoreceiver \((R = 27 [V \times W^{-1}])\) and 15 ps rise time, and the detected voltage was sampled by a real-time digitizing oscilloscope at 4 Giga-samples per second. The power spectral density of the sampled trace was calculated in real time by the digital oscilloscope and monitored near a frequency of \(2 \times 139.6 \text{ MHz}\). This frequency corresponds to a resonance of guided acoustic mode TR\(_2\). The contribution of radial modes to the forward SBS process at that frequency is negligible. The magnitude of the power spectral density peak was used as feedback for polarization adjustments.

The output probe wave in the second analysis branch passed through a polarization beam splitter. Another polarization controller at the common input port of the beam splitter adjusted the state of polarization of the probe wave. The state was chosen so that when the pump pulses were turned off, the probe wave was equally split between the two output ports of the beam splitter. A second photoreceiver (with the same responsivity and rise time) detected the probe wave at output port 1 of the beam splitter. Detected signals represented cross-polarization coupling of the probe wave along the fiber under test. The detector voltage was sampled by a second channel of the digitizing oscilloscope, and the power spectral density of collected traces was calculated digitally. The power spectral density was monitored near the same central radio frequency as above. In addition to the two probe detection channels, a tap coupler at the output of the fiber under test routed 1% of the power of both pump and probe to a polarization analyzer instrument. The analyzer recorded the states of polarization on the Poincare sphere.

3. Results

3.1. Stimulation of Torsional-Radial Modes by Linearly Polarized, Coaligned Pump Waves

Consider two continuous optical pump tones that are linearly copolarized and copropagate along an SMF in the positive \(z\) direction. We denote the direction of electric fields of the two pump waves as the transverse \(\hat{s}\) axis, and the orthogonal transverse direction as \(\hat{t}\). The optical frequencies of the two tones are \(\omega_p \pm \frac{1}{2} \Omega\), where \(\omega_p\) is a central frequency and \(\Omega\) represents a radio-frequency detuning variable. The optical power of the two tones combined includes constant terms and a beating pattern. The beating term is propagating with frequency \(\Omega\), axial wavenumber \(K = n\Omega/c\) and magnitude of \(P(\Omega) = 2n\epsilon_0 c A_1 A_2^* [W]\). Here \(n\) is the effective index of the optical mode, \(\epsilon_0\) is the vacuum permittivity, \(c\) represents the speed of light in vacuum, and \(A_1, A_2\) are the complex magnitudes \([V]\) of the field components of higher and lower frequencies, respectively. The transverse profile of the single optical mode is noted by \(E_1(r) [m^{-1}]\), where \(r\) is the radial transverse coordinate. It is normalized so that \(2\pi \int |E_1(t)|^2 dr = 1\). We also assume that the pump tones are undepleted, and neglect for the time being the possible exchange of power between the two along \(\hat{z}\).

The electro-strictive force per unit volume \(\vec{F}\) associated with the pump tones consists of transverse components in the radial and azimuthal directions\(^{[1–6]}\):

\[
\vec{F}(r, \phi, z, t) = \frac{1}{4nc} \vec{j} \cdot \vec{F}(r, \phi) \vec{P}(\Omega) \exp(jKz - j\Omega t) + c.c. \quad (2)
\]

\[
\vec{j}(r, \phi) = - (2a_1 + 4a_2) \frac{\partial E_r(r)}{\partial r} E_r(r) \hat{r} - 2a_1 \frac{\partial E_\phi(r)}{\partial r} E_\phi(r) \quad (3)
\]

In the above equations \(\phi\) is the transverse azimuthal coordinate with respect to the \(\hat{x}\) axis, \(\hat{r}\) and \(\hat{\phi}\) denote unit vectors in the radial and azimuthal directions, respectively, and \(z\) is the axial coordinate, and \(t\) stands for time. The coefficients \(a_{1,2}\) are drawn from elements of the photoelastic tensor \(p\) of the material:\(^{[1–6]}\) \(\epsilon_{1,2} = 0.66\) and \(a_{2,1} = -1.19\). Note that \(\vec{F}(\Omega)\) in Equation (2) is not restricted to the power of beating between two continuous waves only. It may also represent the Fourier transform of the instantaneous optical power of modulated coherent or incoherent light sources\(^{[16,18,38]}\).

The force per unit volume \(\vec{F}\) propagates with the same phase velocity \(c/n\) of guided light.

The transverse dependence \(\vec{j}(r, \phi)\) of the force per unit volume in Equation (3) consists of two terms. The first term \(\vec{j}_0(r)\) depends on the radial coordinate \(r\) only, and points in the radial direction \(\hat{r}\) only. This term drives the oscillations of purely radial guided acoustic modes \(R_{1m}\).\(^{[1–4]}\) The second term \(\vec{j}_2(r, \phi)\) depends on both \(r\) and \(\phi\), includes components in both the radial and azimuthal directions, and is characterized by twofold azimuthal symmetry. It can therefore stimulate the oscillations of torsional-radial guided acoustic modes of the same symmetry, namely TR\(_{2m}\) modes. If the pump tones are polarized along the \(\hat{y}\) axis instead, the argument \(2\phi\) in Equation (3) is replaced with \(2(\hat{y} \cdot \hat{\phi} - \hat{z} \cdot \hat{r})\) and \(\vec{j}_2(r, \phi)\) changes sign.

The stimulated acoustic waves propagate in the positive \(\hat{z}\) direction with axial wavenumber \(K\) and frequency \(\Omega\). The material displacement vector \([m]\) of the acoustic wave may be expressed as\(^{[1–6]}\):

\[
\vec{U}_{2m}(r, \phi, z, t) = B_{2m}(\Omega) \vec{U}_{2m}(r, \phi) \exp(jKz - j\Omega t) + c.c. \quad (4)
\]

In Equation (4), \(B_{2m}(\Omega) [m^2]\) denotes the modal displacement magnitude (see later), and the transverse displacement profile \(\vec{U}_{2m}(r) [m^{-1}]\) is normalized so that \(\int |\vec{U}_{2m}(r, \phi)|^2 dr \, d\phi = 1\). Each \(TR_{2m}\) mode is characterized by a cutoff frequency \(\Omega_{2m}\), below which it does not propagate. The cut-off frequency is given by the \(m\)-order solution to the boundary conditions equations of a silica rod of radius \(a\), with zero stress at the outer boundary\(^{[33,39,40]}\) (see Supporting Information S1 for the eigen-value equation). Once found, the cut-off frequencies \(\Omega_{2m}\) determine the transverse profiles \(\vec{U}_{2m}(r, \phi)\).\(^{[33,39,40]}\)
For calculations of \( u^{(i)}_{2,m}(r) \) and \( u^{(ii)}_{2,m}(r) \), see Supporting Information S1.[33,39,40]

The modal oscillations may make take place through two degenerate, spatially orthogonal profiles: one characterized by azimuthal dependence according to the upper terms in the curled brackets of Equation (5), and another by the lower terms. The second profile is rotated by \( \pi/4 \) radians with respect to the first. In the latter solution, radial displacement is maximal at \( \phi = \pm \pi/4 \). We refer to the transverse directions of maximum radial displacement as the principal axes of the guided acoustic TR\(_{2,m}\) mode. The principal axes are therefore \( \hat{x} \) and \( \hat{y} \) for the first possible solution, and \( \hat{z} \) for the second. Figure 2 shows the normalized calculated transverse profile of mode TR\(_{2,1}\) (cutoff frequency near \( 2\pi \times 139.6 \text{ MHz} \)), with principal axes along \( \hat{x} \) and \( \hat{y} \) directions. Note that the principal axes are the same for \( \hat{x} \) or \( \hat{y} \) polarized pump waves. Supporting Video S1 shows calculations of the normalized instantaneous density variations: \( \nabla \cdot \mathbf{U}_{1,1}/\rho \), in the fiber cross-section. Here \( \rho \) denotes the density of silica.

The magnitude \( B_{2,m}(\Omega) \) of the stimulated acoustic oscillations of mode TR\(_{2,m}\) is given by [1-6]

\[
\begin{align*}
B_{2,m}(\Omega) &= \frac{1}{4\pi c_0} \iint_{Q_{2,m}} \mathbf{u}_{2,m}(r, \phi) \cdot \mathbf{f}_s(r, \phi) \, r \, dr \, d\phi \, P(\Omega) \\
&= \frac{1}{4\pi c_0} Q_{2,m} H_{2,m}(\Omega) \tilde{P}(\Omega)
\end{align*}
\]

(6)

The stimulation efficiency scales with the spatial overlap integral between the transverse profiles of the driving force and the modal displacement [1-6] \( Q_{2,m} \equiv \iint \mathbf{u}_{2,m}(r, \phi) \cdot \mathbf{f}_s(r, \phi) \, r \, dr \, d\phi \). \( \Gamma_{2,m} \) denotes the modal linewidth, which also signifies the decay rate of acoustic intensity. For bare fibers in air, there is little loss of acoustic energy to the surroundings and the linewidths \( \Gamma_{2,m} \) are determined entirely by internal acoustic dissipation in the silica cladding. The modal line widths are evaluated experimentally. For brevity, we represent hereunder the radio-frequency response of the modal stimulation by \( H_{2,m}(\Omega) \equiv 1/(\Omega^2 + \Omega^2 \Omega - j\Omega \Omega) \). The stimulation of acoustic mode TR\(_{2,m}\) is maximal at its cutoff frequency \( \Omega = \Omega_{2,m} \).

The azimuthal dependence of the driving force \( \mathbf{f}_s(r, \phi) \) (see Equation 3) matches that of \( u_{2,m}(r, \phi) \) with principal axes \( \hat{x} \) and \( \hat{y} \) (Equation 3). The pump tones may therefore stimulate the oscillations of the TR\(_{2,m}\) mode with one of its principal axes aligned with their common linear polarization. On the other hand, the profile \( u_{2,m}(r, \phi) \) with principal axes along \( \hat{z} \) leads to \( Q_{2,m} \) = 0. This profile of the guided acoustic mode cannot be driven by coaligned, linearly polarized pump waves.

3.2. Stimulation of Torsional-Radial Modes by Linearly Polarized, Orthogonal Pump Waves

Consider next the case where one optical pump tone of frequency \( \omega_p = \frac{1}{2} \Omega \) is linearly polarized in the \( \hat{x} \) direction as before, whereas the pump wave frequency of \( \omega_p = \frac{1}{2} \Omega \) is \( \hat{y} \) polarized. Due to the orthogonal polarizations, the combined intensity of the two pump waves does not include a beating term at frequency \( \Omega \). However, electrostriction is a tensor characteristic of optomechanical interaction that goes beyond the gradients of scalar intensity alone. [6,22,23] Therefore, the two waves do induce an electro-strictive driving force per unit volume that oscillates at \( \Omega \), of the following form [5]

\[
\mathbf{f}_o(r, \phi, z, t) = \frac{1}{4\pi c_0} \int \mathbf{r}(r, \phi) \, P(\Omega) \exp(j\Omega z - j\Omega t) + c.c.
\]

(7)

\[
\int \mathbf{f}_o(r, \phi) = 2a_i \left[ E_x(r) \frac{\partial E_z(r)}{\partial y} + E_z(r) \frac{\partial E_x(r)}{\partial y} \right]
\]

(8)
Here we denote \( \tilde{P} (\Omega) = 2n\varepsilon_0 c A^*_t \) as before, even though the term does not signify intensity beating between orthogonally polarized pump tones in the context of this discussion. The electrostrictive force induced by orthogonal pump waves has been considered in specially nanostructured fibers and polarization-maintaining fibers,\(^{16,24}\) but not in SMF. Comparison of Equations (8) and (3) reveals that the driving force induced by the two orthogonal pump tones matches \( f_j (r, \phi) \), with \( \pi/4 \) radians rotation. We therefore expect that the two pump waves may stimulate \( TR_{2,m} \) modes, with the same magnitudes expressed in Equation (6) above. This time, however, the transverse profile of the driving force matches \( u_{2,m} (r, \phi) \) with principal axes along the \( \hat{e}_{x,y} \) directions, rather than \( \hat{x} \) and \( \hat{y} \). Note also that the driving force induced by the orthogonal, linearly polarized pump waves does not include a radially symmetric term in the form of \( f_0 (r) \). Pump waves of linear and orthogonal polarizations therefore do not stimulate the radial acoustic modes \( R_{0,m} \).

### 3.3. Scattering of Optical Probes by Torsional-Radial Modes

The material displacement of \( TR_{2,m} \) modes is associated with strain in the fiber medium, which propagates with frequency \( \Omega \) and wavenumber \( K \). Strain, in turn, induces photoelastic perturbations to the local dielectric tensor across the fiber: \( \Delta \varepsilon_{2,m} (r, \phi, z, t) \).\(^{1-6}\) The effect of the dielectric perturbations on the propagation of optical waves is governed by their spatial overlap with the optical mode \( E_z (r) \):\(^{1-6}\)

\[
\Delta \varepsilon_{2,m} (z, t) = \int \int \Delta \varepsilon_{2,m} (r, \phi, z, t) |E_z (r)|^2 r dr d\phi
\]

(9)

With no loss of generality, we consider below \( TR_{2,m} \) modes with principal axes \( \hat{x} \) and \( \hat{y} \). The position-averaged dielectric perturbations tensor for these modes, in the basis of the principal axes, is of the following form (see Supporting Information S2):

\[
\Delta \varepsilon_{2,m} (z, t) = \Delta \varepsilon_{2,m} (\Omega) \exp (jKz - j\Omega t) \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} + c.c
\]

(10)

\[
\Delta \varepsilon_{2,m} (\Omega) = Q_{\text{PE}}^{(2,m)} B_{2,m} (\Omega) = \frac{1}{4n\varepsilon_0} Q_{\text{PE}}^{(2,m)} Q_{\text{PE}}^{(2,m)} H_{2,m} (\Omega) \tilde{P} (\Omega)
\]

(11)

Note that the dielectric perturbations \( \Delta \varepsilon_{2,m} (z, t) \) propagate along the fiber with the same phase velocity as guided light. The scattering of light by these perturbations is therefore inherently wavenumber matched. The overlap integral \( Q_{\text{PE}}^{(2,m)} \) of photoelastic perturbation is given by (see Supporting Information S2)

\[
Q_{\text{PE}}^{(2,m)} = \frac{\pi}{2} / a_t (r) \left( \frac{du_{z,m}^{(0)}}{dr} + \frac{du_{z,m}^{(0)}}{dr} + \frac{u_{z,m}^{(0)}}{r} + \frac{u_{z,m}^{(0)}}{r} \right) |E_z (r)|^2 r dr
\]

(12)

The definition allows for possible small-scale differences between the photoelastic parameters of core and cladding.

The dielectric perturbations tensor of Equation (10) signifies photoelastic birefringence along the principal displacement axes of the \( TR_{2,m} \) modes. An optical probe field that is polarized along the \( \hat{x} \) principal axis of material displacement experiences effective index disturbance which propagates with frequency \( \Omega \) and wavenumber \( K \), and magnitude \( \Delta n_{x,m} (\Omega) = \Delta \varepsilon_{2,m} (\Omega) / 2n \) (note that \( \Delta n_{x,m} (\Omega) \ll 1 \)). Probe light aligned with the orthogonal principal axis \( \hat{y} \) is subject to index variations of the same \( \Omega \) and \( K \), but with the opposite sign: \( -\Delta n_{x,m} (\Omega) \). Since \( K = n\Omega/c \), and neglecting chromatic dispersion, the index perturbations are wavenumber-matched with the probe.\(^{1-6}\) Following propagation in a fiber of length \( L \), the instantaneous phases of \( \hat{x} \) and \( \hat{y} \) polarized probe waves are given by\(^{41}\)

\[
\Delta \phi_{2,m}^{(x,y)} (z) = \pm k_0 \Delta n_{x,m} (\Omega) \exp (jKz - j\Omega t) + c.c
\]

(13)

Here \( k_0 \) is the vacuum wavenumber of the probe wave. Equation (13) defines the opto-mechanical nonlinear coefficient of mode \( TR_{2,m} \), in units of \( W^{-1} \times m^{-1} \):\(^{41}\)

\[
\gamma_{2,m} (\Omega) = \frac{k_0 Q_{\text{PE}}^{(2,m)} Q_{\text{PE}}^{(2,m)}}{8\pi^2 c}\rho H_{2,m} (\Omega)
\]

(14)

The coefficient assumes its maximum value \( \gamma_{2,m} (\Omega) \) at the cut-off frequency \( \Omega = \Omega_{2,m} \):

\[
\gamma_{2,m} (\Omega) = \int \int \rho (\Omega, \mu) \frac{d\Omega}{d\mu} \frac{d\mu}{d\Omega}
\]

(15)

Consider next optical probe waves that are polarized with equal-magnitude projections on the two principal axes. We denote the unit Jones vector of these probe waves as \( \hat{e}_{2,m} = (1/\sqrt{2}) [ 1 \exp(i\alpha) \] , where \( \alpha \) is an arbitrary relative phase. The dielectric perturbations of Equation (10) partially scatter the probe waves to their orthogonal states: \( (1/\sqrt{2}) [ 1 - \exp(i\alpha) \] , for any choice of \( \alpha \). The instantaneous probe field that is scattered to the orthogonal polarization equals:

\[
\Delta A_{2,m} (\Omega) = \gamma_{2,m} (\Omega) \tilde{P} (\Omega) \cdot A_{2,m} \exp (jKz - j\Omega t) + c.c.
\]

(16)

where \( A_{2,m} \) is the input magnitude of the probe wave. For those input states, cross-polarization coupling takes place instead of phase modulation. Probe waves of arbitrary input polarization would undergo a combination of phase modulation and cross-polarization coupling. If the principal axes of the \( TR_{2,m} \) mode are randomly scattered along a series of repeating measurements, the ensemble average of photoelastic scattering for any input probe polarization would cancel out to zero. In contrast to the torsional-radial modes, the tensors of dielectric perturbations \( \Delta \varepsilon_{2,m} (z, t) \) due to the radial acoustic modes \( R_{0,m} \) are proportional to the identity matrix \( I \).\(^{1,2}\) Radial modes therefore induce the same phase modulation on probe waves of all input polarizations.

The photoelastic perturbations also couple between the optical power levels of the two pump waves \( P_{2,1} = 2\pi\varepsilon_0 c |A_{1,2}|^2 \)\(^{18}\)

\[
\frac{d}{dz} P_1 (z) = -2\pi \text{Im} \left[ \gamma_{2,m} (\Omega) \right] P_1 (z) P_2 (z)
\]

(17)
\[
\frac{d}{dz} P_2(z) = 2 \text{Im} \left\{ \gamma_{2,m} (\Omega) \right\} P_1(z) P_2(z) \quad (18)
\]

The imaginary part of \( \gamma_{2,m} (\Omega) \) is positive. The forward SBS process therefore leads to the attenuation of the higher-frequency pump wave, and the amplification of the lower frequency one.\(^{[18]}\) Forward SBS processes involving \( \text{TR}_{2,m} \) modes were characterized experimentally through measurements of their effects on pump and probe waves, as detailed next.

### 3.4. Experimental Results: Stimulation of Torsional-Radial Modes

In a first set of measurements, a 30 m long standard SMF under test was placed within a Sagnac interferometer loop,\(^{[16,33,34]}\) (see the Experimental Section). The fiber was stripped of its protective polymer coating to obtain stronger forward SBS interactions. Polarized pump pulses of 1 ns duration, 5 µs period and 100 mW average power were launched into the fiber, in the clockwise direction of propagation only. An optical bandpass filter kept the pump pulses from reaching the loop output. Continuous probe light of a different wavelength was launched into the loop in both directions. The probe wave in the clockwise direction copropagated with the pump pulses and acquired phase modulation due to acoustic waves, whereas the probe in the counter-clockwise direction was largely unaffected due to lack of phase matching.\(^{[34]}\)

The two replicas of the probe field were mixed together at the loop output. The beating converted the nonreciprocal phase modulation imposed by the acoustic waves into an intensity signal. The output probe wave was detected by a broadband photoreceiver. For small signals, the modulation of the detector voltage was proportional to the phase modulation of the clockwise-propagating probe. The voltage was sampled by a digitizing oscilloscope for further offline processing.

Figure 3a shows measurements and calculations of the normalized phase modulation spectrum of the probe wave, as functions of radio frequency \( \Omega \). The spectrum consists of sparse and narrow resonances, corresponding to \( R_{0,m} \) and \( \text{TR}_{0,m} \) modes. The modal linewidths used in calculations were fitted as a quadratic function of frequency, based on the measured spectrum.\(^{[32]}\) Agreement between model and experiment is very good. The magnitudes of peaks corresponding to \( R_{0,m} \) modes were unaffected by the specific polarization of the input pump pulses, whereas those associated with \( \text{TR}_{0,m} \) modes exhibited polarization dependence, as expected. The polarization of the pump pulses was adjusted to maximize the phase modulation due to \( \text{TR}_{0,m} \) modes. The largest nonlinear coefficient \( \chi^{(2)}_{2,m} \) for torsional-radial modes was calculated as 3 \( \text{W}^{-1} \text{m}^{-1} \), as opposed to 20 \( \text{W}^{-1} \text{m}^{-1} \) for the strongest radial modes. Results are shown on logarithmic scale to emphasize the weaker contributions of \( \text{TR}_{2,m} \) modes. Figure 3b presents another experiment in which the polarization of pump pulses was randomly scrambled among repeating acquisitions. The contributions of \( \text{TR}_{2,m} \) modes to the phase modulation spectrum cancel out in this case, while those of \( R_{0,m} \) modes remain, in agreement with analysis and previous observations.\(^{[16,33,34]}\)

In the next set of experiments, two continuous pump tones were used instead of short and isolated pulses. The states of polarization of the two tones at the input end of a 6 m long bare fiber under test were adjusted to be linear and orthogonal (see the Experimental Section). The optical frequencies of the two pump waves were tuned separately using single-sideband electro-optic modulators to obtain a precise and variable difference \( \Omega \). In addition, the intensities of the two waves were modulated by respective signals of low radio frequencies \( f_{1,2} \), drawn from two output ports of a lock-in amplifier. The instantaneous magnitude of acoustic waves stimulated by the two pump tones was therefore modulated at low frequencies \( f_1 \pm f_2 \). The stimulation is accompanied by the coupling of optical power between the pump tones, as discussed above. The intensities of the two pump waves at the output of the fiber under test were therefore modulated at frequencies \( f_1 \pm f_2 \) as well.\(^{[37]}\) A polarization beam splitter at the output end of the fiber was used to select a single pump tone, which was then detected by a photoreceiver. The lock-in amplifier monitored the magnitude of the detected voltage component at the sum frequency \( f_1 + f_2 \).

Figure 3c shows the normalized magnitude of the lock-in amplifier output signal as a function of \( \Omega \), alongside corresponding calculations. Spectral peaks matching the cut-off frequencies of \( \text{TR}_{0,m} \) modes are observed in the measurements, whereas those associated with the radial \( R_{0,m} \) modes are eliminated (see also panel (a)), in agreement with analysis. The results constitute a first demonstration of stimulated Brillouin coupling between orthogonally polarized waves in SMF.

### 3.5. Experimental Results: Scattering by Torsional-Radial Modes

A final set of experiments examined the polarization dependence of probe waves scattering by a torsional-radial mode. The setup is described in detail in the Experimental Section. Short pump pulses were launched into a 30 m long section of bare SMF under test, in a similar manner to the Sagnac loop measurements presented earlier. The polarization of the pump pulses was adjusted by a manual polarization controller. A continuous probe wave of different wavelength copropagated alongside the pump pulses. The input state of polarization of the probe was independently controlled as well. A tunable optical bandpass filter blocked the pump pulses at the output end of the fiber. The probe wave at the output was split in two analysis branches. One replica was reflected by a narrow fiber Bragg grating filter. The exact wavelength of the probe was aligned with a maximum slope of the grating spectrum. Reflection from the grating converted phase modulation of the probe wave by guided acoustic waves to an intensity reading. The reflected waveform was detected by a broadband photoreceiver and sampled by one channel of a digitizing oscilloscope.

The output probe in the second detection branch passed through a polarization beam splitter. Another polarization controller aligned the probe for equal projections on its two output ports. A second photoreceiver at output port 1 of the beam splitter was used to identify cross-polarization coupling of the probe wave due to guided acoustic waves. The detector output was sampled by a second channel of the oscilloscope. The radio frequency power spectral densities of the two sampled signals were digitally calculated. The power spectral densities near frequency \( \Omega_{2,2} = 2 \pi \times 139.6 \text{ MHz} \) were monitored. This frequency corresponds to a resonance of mode \( \text{TR}_{2,2} \), with little forward SBS contribution.
Figure 3. Stimulation of guided acoustic waves in standard single-mode fiber. a) Measured (solid blue) and calculated (dashed red) spectra of probe wave phase modulation due to guided acoustic modes. The acoustic modes were stimulated by short pump pulses. The spectrum consists of two series of sparse and narrow resonances, corresponding to purely radial $R_{0,m}$ modes and torsional-radial modes with twofold azimuthal symmetry (TR$_{2,m}$ modes). The polarization of the input pump pulses was adjusted to maximize the stimulation of the torsional-radial modes. Agreement between model and measurement is very good. b) Same as panel (a), with the polarization of the pump pulses scrambled among repeating acquisitions. Scrambling removes the contributions of TR$_{2,m}$ modes from the ensemble average of repeating acquisitions. Panels (a) and (b) are shown in dB scale to emphasize the weaker contributions of TR$_{2,m}$ modes. c) Measured (solid blue) and calculated (dashed red) normalized spectra of forward SBS coupling of optical power between two pump tones of orthogonal linear polarizations (linear scale). The spectrum consists of TR$_{2,m}$ modes only. The $R_{0,m}$ modes were not stimulated.

from any of the radial modes (see also Figure 3). In addition, the states of polarizations of the pump and probe waves at the output of the fiber under test were recorded by a polarization analyzer.

In a first acquisition, the states of polarization of the input pump and probe were adjusted until maximum phase modulation at $\Omega_{2,7}$ was identified at the Bragg grating output. According to the analysis of Sections 3.2 and 3.4, maximum should be reached when two conditions are met: i) the pump pulses are linearly polarized for the strongest stimulation of the acoustic mode; and ii) the probe polarization is aligned either with that of the pump pulses, or with the orthogonal linear state. Figure 4a, b (red traces) show the normalized power spectral densities of the fiber Bragg grating and polarization beam splitter measurement channels, respectively. Maximum phase modulation of the probe wave is accompanied with weak cross-polarization coupling. Figure 4c shows the states of polarization of the pump and probe waves. Maximum phase modulation is obtained at two pump polarizations: one aligned with the probe wave and the other orthogonal, as anticipated.

In a second measurement, the pump pulses polarization was adjusted for maximum cross-polarization coupling of the probe wave (see Figure 4b, blue trace). Figure 4c shows the two pump polarizations. The states of polarization form $\pi/2$ angles with that of the probe on the Poincare sphere, in agreement with expectations. In these settings, phase modulation of the output probe is significantly reduced (Figure 4a, blue trace). Figure 4d
Figure 4. Scattering of probe waves by torsional-radial guided acoustic modes. a) Measured normalized power spectral density of probe wave phase modulation due to guided acoustic mode \( TR_{2,7} \) at frequency 139.6 MHz. b) Measured power spectral density of cross-polarization coupling of the probe wave due to the same guided acoustic mode. The acoustic wave was stimulated by short pump pulses. In both panels, red traces correspond to the alignment of the pump input polarization for maximum phase modulation of the probe wave, and blue traces were taken when the pump polarization was adjusted for maximum cross-polarization coupling of the probe. Maximum phase modulation corresponds to weak residual cross-polarization coupling, and vice versa. The sinc spectral shapes correspond to a temporal integration window of 5 \( \mu \)s. c) Measured states of polarization of the probe wave (black) and pump pulses at the output of the fiber under test. The pump polarization was adjusted for maximum phase modulation of the probe wave (red), or maximum cross-polarization coupling of the probe wave (blue). Maximum phase modulation is obtained when the polarizations of pump and probe are either aligned or orthogonal. At maximum cross-polarization coupling, the pump and probe polarizations form a \( \pi/2 \) angle on the Poincare sphere. d) Measured normalized power spectral density of cross-polarization coupling of the probe wave, over broader frequency range. In the blue trace, the polarization of pump pulses was adjusted for maximum cross-polarization coupling, similar to the blue traces of panels (a) and (b). The spectrum consists entirely of contributions of \( TR_{2,m} \) modes only, without \( R_{0,m} \) modes. In the red trace, the pump polarization was adjusted for maximum phase modulation of the output probe wave (see red traces of panels (a) and (b)). No cross-polarization coupling is observed in this case.

3.6. Stimulation of Torsional-Radial Modes by Circularly Polarized Pump Tones

Consider two continuous optical pump tones with circular polarization, expressed by the unit Jones vector \( \hat{e}_C = \frac{1}{\sqrt{2}} (\hat{x} + j\hat{y}) \). The two tones induce an electrostrictive force which propagates in the positive \( \hat{z} \) direction with frequency \( \Omega \) and wavenumber \( K \) as before. Below we only relate to the force term of transverse profile \( f_2(r, \phi) \) with twofold azimuthal dependence and disregard the radially symmetric component (see Equation 3). The term \( f_2(r, \phi) \) consists of four contributions. Two of them are associated with
interactions between linearly copolarized components of the two pump tones. The $\hat{x}$ components of the two pumps give rise to a force term of the following transverse profile:

$$f_2(x, \phi) = -a_1 \frac{\partial E_r(r)}{\partial r} E_t(r) \left( \cos(2\phi) \hat{r} - \sin(2\phi) \hat{\phi} \right)$$ (19)

The projections of the two pump waves on the $\hat{x}$ axis contribute a force term with the profile

$$f_2(x, \phi) = -a_1 \frac{\partial E_r(r)}{\partial r} E_t(r) \left( \cos(\phi - \frac{\pi}{2}) \right) \hat{r} - \sin(\phi - \frac{\pi}{2}) \hat{\phi} = -f_2(\phi)$$ (20)

The two components therefore cancel out. In addition, the driving force also includes two contributions which stem from the interactions between the $\hat{x}$ component of one pump and the $\hat{y}$ component of the other

$$f_2(x, \phi) = ja_1 \frac{\partial E_r(r)}{\partial r} E_t(r) \left( \sin(2\phi) \hat{r} + \cos(2\phi) \hat{\phi} \right)$$ (21)

$$f_2(x, \phi) = -ja_1 \frac{\partial E_r(r)}{\partial r} E_t(r) \left( \sin(2\phi) \hat{r} + \cos(2\phi) \hat{\phi} \right)$$ (22)

Those two terms cancel each other as well. The same outcome is reached for two pumps aligned with the opposite circular polarization $\hat{e}_C = (1/\sqrt{2}) (\hat{x} - \hat{y})$. Therefore, two pump tones of a common circular polarization do not provide a driving force for the stimulation of TR$_{2,m}$ modes.

We address next the scenario in which the upper frequency pump wave is polarized at $\hat{e}_C$, and the lower frequency one at $\hat{e}_C$. In this case, the force components of Equations (20) and (22) change sign, and the overall electrostrictive driving force no longer equals zero

$$f_2(x, \phi) = -2a_1 \frac{\partial E_r(r)}{\partial r} E_t(r) \left( \cos(2\phi) \hat{r} - \sin(2\phi) \hat{\phi} \right) + j2a_1 \frac{\partial E_r(r)}{\partial r} E_t(r) \left( \sin(2\phi) \hat{r} + \cos(2\phi) \hat{\phi} \right)$$ (23)

The electrostrictive force may therefore stimulate the oscillations of TR$_{2,m}$ modes in both azimuthal forms (see Equation 5). The two modal solutions are driven with equal magnitudes, and with a phase offset of $\pi/2$. The overall displacement of the acoustic oscillations may be expressed as:

$$U_{2,m}(x, \phi, z, t) = B_{z,m}(\Omega) \exp(jKz - j\Omega t) \times \left\{ u'^{(\omega)}_{1,m}(r) \left[ \cos(2\phi) - jsin(2\phi) \right] \hat{r} + u'^{(\omega)}_{2,m}(r) \left[ -\sin(2\phi) - j\cos(2\phi) \hat{\phi} \right] + c.c. \right\} \times \exp(j2\phi) \exp(jKz - j\Omega t) + c.c.$$(24)

The modal magnitude $B_{z,m}(\Omega)$ above remains that of Equation (6). The material displacement of Equation (24) is therefore rotating in the $\hat{e}_{RC}$ direction with twofold azimuthal periodicity, representing an acoustic vortex beam. [25–30] Supporting Video S2 shows calculations of the normalized instantaneous density variations in a TR$_{2,7}$ mode vortex beam: $V \cdot U_{2,7}/\rho$. If the polarizations of the higher and lower frequency pump waves are switched, the azimuthal dependence in Equation (24) would take up the form of $\exp(-j2\phi)$ instead.

The stimulation of an acoustic vortex beam may be interpreted as follows:[25–30] The forward SBS process eliminates a photon of frequency $\omega_p + \frac{\Omega}{2}$ and unit angular momentum in one direction, associated with its polarization degree of freedom. The same process generates a photon of frequency $\omega_p - \frac{\Omega}{2}$ with a unit angular momentum in the opposite direction. The overall angular momentum is conserved by the orbital angular momentum of the stimulated acoustic wave, which represents two units in the same direction of the eliminated, higher-frequency photon. [25–30]

The Brillouin stimulation therefore transfers angular momentum between the polarization degree of freedom of the light field and the acoustic wave.

4. Discussion

This work applies vector theories of SBS,[6,22,23] previously used in the study of more complex waveguide geometries,[6,22–24] to the important specific case of forward SBS in standard SMF. Despite the symmetry and simplicity of the SMF waveguide, the analysis brings up several properties of the process that cannot be accounted for by scalar models and were not considered in previous studies. Torsional-radial guided acoustic modes of twofold azimuthal symmetry may be stimulated by a pair of optical pump waves of either equal or orthogonal linear polarizations. This property is in marked contrast to radial modes, which may be stimulated by copolarized pump waves only.

The principal axes of material displacement in the acoustic oscillations of torsional-radial modes depend on the polarizations of the pump wave. When the pump waves are copolarized, one principal axis is aligned with their linear state of polarization. If the two pumps are orthogonal, the principal axes are oriented at 45° with respect to their two polarizations. Optical probe waves that are aligned with either of the two axes undergo photelastic phase modulation. If the probe wave is polarized with equal projections on the two axes, cross-polarization coupling takes place instead. Predictions were corroborated by experiments, with very good agreement. The analysis of probe waves scattering extends upon previous studies of birefringence induced by torsional-radial modes.[11] In the spontaneous scattering regime studied by Shelby et al.,[11] acoustic waves pre-exist at all possible azimuthal orientations. Hence every input state of an optical probe wave can be partially scattered to the orthogonal polarization, with equal probabilities. In the stimulated effect studied here, one can identify and even predict specific states of the input optical probe that would undergo maximal or minimal polarization rotations.

The measurements presented a first report of stimulated Brillouin scattering between two orthogonal pump waves in SMF. Such a demonstration has yet to be provided, in the forward or
backward directions of Brillouin scattering. The results also include the selective excitation of torsional-radial acoustic modes and selective scattering by those modes, without the purely radial ones. Since forward SBS through radial modes is stronger in SMF, the contributions of torsional-radial modes are often masked out. The boundary conditions at the outer edge of the fiber cladding, and particularly at the interface between cladding and coating, could be different between radial and torsional-radial modes. Therefore, the study of torsional-radial modes may prove helpful in new concepts of optical fiber sensors based on forward SBS, which address media beyond the cladding and coating and the properties of the coating itself.

The formalism predicts special properties of forward SBS processes driven by circularly polarized pump waves. Two pump waves of the same circular polarization may not stimulate torsional-radial acoustic modes. However, if the two waves are of opposite circular polarizations the stimulation of these modes becomes possible. The principal axes of the stimulated acoustic wave in this case would be rotating, giving rise to an acoustic vortex beam. The rotation of the displacement profile signifies the transfer of angular momentum between the polarization degree of freedom of the light field and the acoustic wave. This rotation of the displacement profile might be observed, for example, in synchronous monitoring of probe waves scattering in multiple cores of a multicore fiber. On a broader context, forward SBS processes driven by pumps of circular polarizations may couple between optical modes of different angular momenta. The proposition of Brillouin stimulation of vortex beams required the extension of scalar models of forward SBS in SMF to vector analysis. Such stimulation mandates the complete degeneracy between two azimuthal orientations of a given torsional-radial mode, which can only occur in a radially symmetric waveguide geometry. The Brillouin stimulation of vortex beams is therefore possible in SMF, and certain classes of multimode and multicore fibers, but it would not take place in the more complex waveguide geometries that were previously analyzed by vector opto-mechanical formalisms.

In conclusion, a more complete description of forward SBS in standard SMF has been established. The process draws renewed interest over recent years. The observations and predictions may open up new directions for research and applications of standard fibers opto-mechanics.

Supporting Information
Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest
The authors declare no conflict of interest.
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