Sub-megahertz spectral dip in a resonator-free twisted gain medium

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Ultra-narrow optical spectral features resulting from highly dispersive light-matter interactions are essential for a broad range of applications such as spectroscopy, slow-light and high-precision sensing. Approaches featuring sub-megahertz or, equivalently, Q-factors up to one billion and beyond, are challenging to obtain in solid-state systems, ultimately limited by loss. We present a novel approach to achieve tunable sub-megahertz spectral features at room temperature without resonators. We exploit gain-enhanced polarization pulling in a twisted birefringent medium where polarization eigenmodes are frequency-dependent. Using Brillouin gain in a commercial spun fibre, we experimentally achieve a 0.72 MHz spectral dip, the narrowest backward Brillouin scattering feature ever reported. Further optimization can potentially reduce the linewidth to <0.1 MHz. Our approach is simple and broadly applicable, offering on-demand tunability and high sensitivity, with a wide range of applications such as microwave photonic filters, slow and fast light, and optical sensing.

Ultra-narrow resonances are highly sought-after for a wide range of applications such as slow-light and information storage, high-precision sensing, microwave photonics, spectroscopy, frequency stabilization, light detection and ranging and optical gyroscopes. Narrowing the linewidth further to the sub-megahertz range (or equivalently, increasing the Q-factors to one billion and beyond) is very challenging, but highly desirable, as it greatly improves the key performance metrics across several applications. For example, when a sub-megahertz transparency is induced via Brillouin scattering using a high-Q silica resonator, it produces slow-light with a five-orders-of-magnitude-higher delay bandwidth product than the previous record reported for Brillouin-based systems. Such favorable performance improvements have stimulated phenomenal progress in obtaining narrow resonances through platforms such as gas-phase atomic systems, photonic crystal cavities, whispering gallery mode and microring resonators. Several approaches for ultra-narrow resonances have been demonstrated using forward SBS in an ultrahigh-Q microresonator, achieving and maintaining triple resonance (one acoustic and two optical resonances) in an ultrahigh-Q resonator is no easy feat. Backward SBS, on the other hand, is easily obtainable in conventional waveguides, but its linewidth is a few tens of megahertz in most solids. Recent efforts made to narrow the SBS feature further include: making a microwave analogue of electromagnetically induced absorption using destructive interference, and combining SBS with an ultrahigh-Q resonator. However, as with other SBS-resonator combination experiments, the one in ref. requires precise alignment between the SBS peak and one of the resonances of the ultrahigh-Q resonator. Obtaining and maintaining such alignment over time can be a major challenge. Moreover, the configuration becomes much more complex with the added resonator.

In this work, we propose an entirely new paradigm to realize a sub-megahertz, tunable spectral feature without using any resonator. We exploit gain-enhanced polarization pulling in a twisted birefringent medium with frequency-dependent polarization eigenmodes. To demonstrate a specific realization, we use backward SBS in a commercial spun birefringent fibre (SBF) and experimentally achieve a 0.72 MHz spectral dip, which is to our knowledge, the narrowest backward SBS spectral feature ever reported. We also demonstrate the on-demand tunability of the linewidth, depth and the spectral location of this dip. Furthermore, the configuration becomes much more complex with the added resonator.

Theoretical framework

An SBF is an elliptically birefringent fibre, fabricated by spinning a birefringent preform while drawing the fibre. It is characterized by its twist rate \( \nu \), and its unspun linear birefringence \( \nu_0 \), where \( \nu \) and \( \nu_0 \) are the twist period and the beat length of the SBF, respectively. Note that although \( \nu \) and \( \nu_0 \) are independent of the frequency, \( \nu \) of the optical field, \( \nu_0 \) and \( \nu \) are dependent.
in this paper, the value of $\gamma_s$ is chosen to be 0.896 (W$^{-1}$m$^{-1}$) (on the same order as the values stated in refs. 39–41). $T_{sp}$ is the polarization transfer matrix for the signal (s) and the pump (p) fields, respectively, in the ($\xi, \eta, z$) coordinate system, given by refs. 43–46.

$$T_{sp}(z) = \begin{bmatrix} \cos(k_{b}(\nu_{sp})z) - i \frac{k_{b}(\nu_{sp})}{k_{b}(\nu_{sp})} \sin(k_{b}(\nu_{sp})z) & -\frac{k_{b}(\nu_{sp})}{k_{b}(\nu_{sp})} \sin(k_{b}(\nu_{sp})z) \\ \frac{k_{b}(\nu_{sp})}{k_{b}(\nu_{sp})} \sin(k_{b}(\nu_{sp})z) & \cos(k_{b}(\nu_{sp})z) + i \frac{k_{b}(\nu_{sp})}{k_{b}(\nu_{sp})} \sin(k_{b}(\nu_{sp})z) \end{bmatrix}$$

where $k_{b}(\nu_{sp}) = \sqrt{k_{b}(\nu_{sp})^2 + k_{f}^2}$ is the elliptical birefringence (resulting from the spinning of a birefringent preform) of an SBF for signal (s) and pump (p) fields, respectively. The eigenmodes of the transfer matrix $T_{sp}(z)$ (refs. 44–46) are denoted by $S_{1}(\nu_{s})$ and $S_{2}(\nu_{s})$ (p) at the signal (pump) frequency, and they are given by:

$$S_{1} = \frac{1}{m_{s}} \begin{bmatrix} i \left( \frac{k_{b}(\nu_{sp})}{k_{b}(\nu_{sp})} \right) + 1 \end{bmatrix}$$

$$S_{2} = \frac{1}{m_{p}} \begin{bmatrix} i \left( \frac{k_{b}(\nu_{sp})}{k_{b}(\nu_{sp})} \right) + 1 \end{bmatrix}$$

$$P_{1} = \frac{1}{m_{p}} \begin{bmatrix} i \left( \frac{k_{b}(\nu_{sp})}{k_{b}(\nu_{sp})} \right) + 1 \end{bmatrix}$$

$$P_{2} = \frac{1}{m_{p}} \begin{bmatrix} i \left( \frac{k_{b}(\nu_{sp})}{k_{b}(\nu_{sp})} \right) + 1 \end{bmatrix}$$

where $m_{s}$ and $m_{p}$ are the normalizing factors for signal (s) or pump (p) eigenmodes. These eigenmodes are independent of the fibre position (z), meaning that polarization eigenmodes launched into the fibre are maintained throughout the fibre. Conversely, non-eigenmode input will experience polarization change along the fibre, even under passive conditions (see the dotted and solid green curve in Fig. 2c). As can be verified, the eigenmodes $S_{1}$ and $P_{1}$ are nearly orthogonal, as are $S_{2}$ and $P_{1}$ (refer to the blue and red dots on the Poincaré sphere in Figs. 2a and 2b). Here we use the word nearly as the pump and signal frequencies are slightly different and thus the eigenmode for the pump is not exactly orthogonal to the eigenmode for the signal. We define a polarization overlap factor (F) to quantify the amount of overlap between signal and pump polarization, where

$$F(z) = \left| \frac{\vec{A}_{s}(z) \cdot \vec{A}_{p}(z)}{|\vec{A}_{s}(z)||\vec{A}_{p}(z)|} \right|^2$$

which remains very small ($<10^{-11}$, see the solid and dashed red curve in the inset of Fig. 2c) when we launch orthogonal eigenmodes $S_{1}(\nu_{s})$ and $P_{1}(\nu_{p})$.

When signal power at frequency $\nu_{s}$ is launched into $S_{1}(\nu_{s})$ without the pump (that is, no SBS gain), its polarization is maintained along the fibre (see the dashed red curve in the inset of Fig. 2c); however, when pump power is launched into $P_{1}(\nu_{p})$, the signal field experiences a weak polarization pulling effect (see the red trace in Fig. 2a and the red curve in Fig. 2c) due to its small overlap $F$ with the pump polarization.
**The polarization eigenmodes of a twisted birefringent medium (for example, SBF) are frequency-dependent.** $S_*(\nu_s)$ is an eigenmode for $\nu_s$, but not for $\nu_s'$. Note that when a non-eigenmode is launched into SBF, its polarization is not preserved along the length of SBF, even under passive conditions (see the dotted and solid green curve in Fig. 2c). So, with a minute deviation in signal frequency from $\nu_s$ to $\nu_s'$, its polarization is no longer an eigenmode for that frequency ($\nu_s'$), resulting in a periodic polarization variation along the fibre. This can be seen from the oscillation in $F$ (dotted and solid green curve in Fig. 2c). This oscillation causes the signal to deviate further, leading to more polarization pulling.

To gain more insights into the behaviour of this spectral dip and how it is affected by linear birefringence and the twist rate, let us define a birefringence-to-twist ratio (BTR = $k_b(\nu_s)/k_t = L/L_s(\nu_s)$). We first analyse the dip depth and linewidth as a function of beat length, at a fixed BTR of 1, meaning that $L_s$ is equal to $L$. As seen in Fig. 3a, the dip disappears if the beat length (and twist period) becomes too large. In the extreme, the spun fibre becomes an SMF.

In the opposite direction, when the beat length (and twist period) decreases, the dip sharpens and deepens, until the dip depth and linewidth converge to limiting values. In other words, for a fixed BTR, when the beat length (and twist period) is sufficiently small, the dip reaches its sharpest limit and no longer narrows or deepens. In the conventional way of plotting the SBS gain as a function of frequency downshift ($\nu$), though the spectral dip is obtained in the optical domain, at $\nu_s$. To gain more insights into the behaviour of this spectral dip and how it is affected by linear birefringence and the twist rate, let us define a birefringence-to-twist ratio (BTR = $k_b(\nu_s)/k_t = L/L_s(\nu_s)$). We first analyse the dip depth and linewidth as a function of beat length, at a fixed BTR of 1, meaning that $L_s$ is equal to $L$. As seen in Fig. 3a, the dip disappears if the beat length (and twist period) becomes too large. In the extreme, the spun fibre becomes an SMF.

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We next analyse the dip behaviour as a function of BTR (Fig. 3b), keeping the beat length sufficiently small ($L_s(\nu_s) = 0.26$ mm). At very low BTRs (for example, $<10^{-5}$) the SBF behaves like a circularly birefringent fibre, whereas at BTRs (for example, $>10^5$) the SBF behaves like a linearly birefringent fibre (such as the PMF). At both extremes, the polarization eigenmodes become independent.

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**Fig. 2 | Simulation results showing the formation of a sub-megahertz spectral dip due to Brillouin gain-enhanced polarization pulling effect in an SBF.**

(a, b) Simulated signal polarization evolution (indicated by the red and green traces with arrows on a Poincaré sphere, where the arrows denote the direction of polarization evolution) along the SBF for signal frequencies $\nu_s = \nu_s - \nu_p$ (denoted by red trace) (a) and $\nu_s' = \nu_s + 0.5$ MHz (denoted by green trace) (b). For both (a) and (b), the input signal polarizations corresponds to the eigenmodes $S_*(\nu_s)$ (denoted by red dot), which is an eigenmode for $\nu_s$, but not for $\nu_s'$. (c) Polarization overlap factor ($F$) of signal and pump polarization states as a function of the length of SBF for input signal polarization $S_*(\nu_s)$ launched at frequencies $\nu_s$ and $\nu_s'$ with gain on ($P_{\text{pump}} = 14.75$ dBm) and off. The inset is a magnified version near $z = 100$ m, showing slight polarization oscillation of a non-eigenmode.

(d) Simulation result demonstrating a spectral dip in SBS gain spectrum of SBF. The gain is plotted as a function of the frequency downshift ($\nu = \nu_s - \nu_p$). The input signal polarization is fixed at $S_*(\nu_s - \nu_p)$ and $\nu_s$ is fixed at 192.97 THz. The linewidth of the dip is 0.28 MHz when measured at 3 dB from the minimum, and the dip depth is 14.3 dB. Simulated signal polarization evolution (indicated by the red and green traces with arrows on a Poincaré sphere, where the arrows denote the direction of polarization evolution) along the SBF for signal frequencies $\nu_s = \nu_s - \nu_p$ (denoted by red trace) (a) and $\nu_s' = \nu_s + 0.5$ MHz (denoted by green trace) (b). For both (a) and (b), the input signal polarizations corresponds to the eigenmodes $S_*(\nu_s)$ (denoted by red dot), which is an eigenmode for $\nu_s$, but not for $\nu_s'$. (c) Polarization overlap factor ($F$) of signal and pump polarization states as a function of the length of SBF for input signal polarization $S_*(\nu_s)$ launched at frequencies $\nu_s$ and $\nu_s'$ with gain on ($P_{\text{pump}} = 14.75$ dBm) and off. The inset is a magnified version near $z = 100$ m, showing slight polarization oscillation of a non-eigenmode.

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The polarization eigenmodes of a twisted birefringent medium (for example, SBF) are frequency-dependent. $S_*(\nu_s)$ is an eigenmode for $\nu_s$, but not for $\nu_s'$. It is important to note that when a non-eigenmode is launched into SBF, its polarization is not preserved along the length of SBF, even under passive conditions (see the dotted and solid green curve in Fig. 2c). So, with a minute deviation in signal frequency from $\nu_s$ to $\nu_s'$, its polarization is no longer an eigenmode for that frequency ($\nu_s'$), resulting in a periodic polarization variation along the fibre. This can be seen from the oscillation in $F$ (dotted and solid green curve in Fig. 2c). This oscillation causes the signal to deviate further, leading to more polarization pulling. Such positive feedback, analogous to laser action, causes its polarization to deviate further, leading to more polarization pulling. This positive feedback, analogous to laser action, causes its polarization to deviate further, leading to more polarization pulling.
of frequency and the dip disappears. On the other hand, when BTR lies in the range of \([0.05, 20]\), the dip linewidth is <1 MHz and the depth is high (>10 dB). Predictably, the dip is narrowest (with a linewidth of ~0.06 MHz) and deepest (with a depth of 17.6 dB) at BTR = 1. This dip linewidth is equivalent to a Q-factor greater than three billion if a resonator was used.

We deduce through these analyses that this spectral dip in the SBS gain spectrum is unique to elliptically birefringent media (such as SBF). It is not observed when both beat length and twist period become large (Fig. 3a), and it also disappears when either linear birefringence or circular birefringence dominates (Fig. 3b). This is why this dip has never been observed in SMF or PMF. This work is the first time such a spectral dip is ever analysed and observed.

Furthermore, the spectral location of this dip can be tuned in real-time (on demand) by changing either the pump frequency or the input polarization (the latter is indicated in Fig. 4a). The linewidth and the depth of the dip can also be tuned—though not independently—by varying the pump power. Under certain pump powers, the dip linewidth narrows and the depth deepens as the pump power increases (Fig. 4b). This behaviour is analogous to the lasing phenomenon where the linewidth of a laser decreases due to the positive feedback received from the gain medium. Beyond a certain pump power, the polarization pulling becomes more pronounced with increasing pump power, even for \(\text{S}_b\), as it is not strictly orthogonal to \(\text{P}_b\) (also see Fig. 2c). This causes the gain at the dip to increase with increasing pump power, and eventually the dip disappears (Fig. 4b).

In summary, by controlling the pump frequency, pump power and signal polarization, one has sufficient degrees of freedom to tune the dip frequency, linewidth and depth in real-time. This has an important practical significance in several applications.

**Experimental results**

For an experimental demonstration, we use a commercial SBF manufactured by IVG Fibre (the SBF is drawn from a rotating glass preform; IVG Fiber model LB1300). Our SBF has a beat length of 26 mm, twist period of 3 mm and length of 900 m (see Supplementary Fig. 7 to learn about the uniformity of our SBF). Note that this fibre does not have the optimal BTR of 1, but it is the only SBF available to us. The experimental set-up (Fig. 5a) splits a continuous wave laser (wavelength = 1,554.616 nm) into two paths. In the upper path, the pump field is amplified and its polarization is adjusted before launching into SBF using a polarization controller. In the lower path, the signal field is amplified and amplitude-modulated to produce two sidebands. The lower frequency sideband is selected by a tunable filter (Ultra-narrow filter with 0.12 nm passband bandwidth from Advanced Optics Solutions). The signal polarization is adjusted before launching into SBF, and its frequency is swept over the Brillouin gain range by sweeping the radio frequency driving the electro-optic modulator.
Due to the high sensitivity of the spectral dip to signal and pump polarization variation, we employ passive polarization stabilization in our experiment. We place most of the components (excluding the laser, amplifiers, spectral filter, radio frequency modulator and power meter) in a passive plexiglass enclosure. This prevents air flow through the arrangement, and makes it less prone to environmental disturbances. The room-temperature variation is kept within 1 °C. We observed that, with such passive stabilization, the dip is stable for the duration of measurement.

The experimental and the simulation results are compared in Fig. 5b, and good agreement between the two is evident. For the simulation result, we included a fibre loss of 5 dB km⁻¹, and a constant amplified spontaneous emission (ASE) noise in the pump field to emulate the experimental conditions. This results in a constant background offset of the Brillouin gain. The inset shows a zoomed-in version of the experimental result near the dip.

For the simulation, we included a constant ASE noise in the pump. The experimental dip being wider than the simulation dip is probably due to the fact that a lower spectral resolution is used in the measurement (0.25 MHz) than in the simulation (0.01 MHz). The experimental gain shape on the wings of the Brillouin gain deviates from the simulation shape, probably due to the following factors: (1) we have not accounted for the nonlinear polarization rotation in our model; (2) we have not accounted for the ASE noise in the signal; (3) our model assumes single, pure polarization input, whereas this is not true in practice, for the pump as well as for the signal. Although these factors are only hypotheses at this stage and need to be rigorously investigated in the future.

Despite the discrepancy at the wings of the spectral gain shape, the simulation captures the ultra-narrow dip feature as well as its tunability, in high consistency with the experimental measurements, thus validating the mechanism we presented here as the cause for the ultra-narrow dip.

The tunability of the spectral location of this dip by changing the input polarization, and the tunability of the linewidth and the depth of dip by varying input pump power are experimentally verified (see Fig. 6a,b). Note, for low pump powers, the gain becomes negative on the wings due to fibre loss, while for high pump powers, the gain has a positive background on the wings due to ASE noise in the pump and the signal. The ASE-induced background can be largely avoided if one uses a high power laser without amplifiers.

The high sensitivity of the spectral location of the dip to variation in input signal polarization, both predicted by our model (Fig. 4a) and observed experimentally (see Fig. 6a and Supplementary Fig. 6), further validates the dip forming mechanism provided in this work and excludes the possibility of spectral hole burning. 

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**Fig. 5 | Experimental demonstration of a sub-megahertz spectral dip in the Brillouin gain spectrum of SBF.**
- **a.** Experimental set-up to measure Brillouin gain: signal frequency is downshifted from the pump by selecting the lower frequency sideband (red) of the modulated signal after the electro-optic modulator. Pump and signal polarizations are controlled by the polarization controllers PC1 and PC3, respectively. CW, continuous wave; RF, radio frequency; EDFA, erbium-doped fibre amplifier; EOM, electro-optic modulator.
- **b.** A comparison of the SBS gain spectrum obtained via simulation and experiment. The simulation and experimental parameters are alike, and they are as following: \( L = 900 \text{ m}, \ L_{\text{air}} = 3 \text{ mm}, \ L_{\text{air}}(\nu_p) = 26 \text{ mm}, \ P_{\text{pump}} = 16.9 \text{ dBm}, \ P_{\text{sig}} = -12 \text{ dBm}, \) and observed experimentally (see Fig. 6a and Supplementary Fig. 6).

**Fig. 6 | Experimental demonstration of the real-time tunability of the dip frequency, linewidth and depth.**
- **a.** Experimental demonstration of the tunability of the spectral position of the dip by varying the input signal polarization, while keeping the pump polarization, \( P_{\text{pump}} (16.9 \text{ dBm}) \) and \( P_{\text{sig}} (-12 \text{ dBm}) \) constant.
- **b.** Experimental demonstration of the tunability of the linewidth and the depth of the dip by varying \( P_{\text{pump}} \) while keeping the input polarizations and \( P_{\text{sig}} \) constant \((-16.2 \text{ dBm})\). The fibre parameters are as following: \( L = 900 \text{ m}, \ L_{\text{air}} = 3 \text{ mm} \) and \( L_{\text{air}}(\nu_p) = 26 \text{ mm} \).
being the mechanism behind the dip (also see Supplementary Fig. 6, in which we compare the SBS gain for co-polarized and orthogonally polarized inputs). Such high polarization-sensitivity cannot be explained by spectral hole burning.

Discussion

As we have seen both theoretically and experimentally, the sub-megahertz spectral dip is a result of polarization pulling in an elliptically birefringent medium. The filtering effect in a birefringent medium is reminiscent of birefringent filters, of which Lyot\(^{52}\) and S\(\acute{\text{a}}\)lc\(\ddot{\text{o}}\)l\(\ddot{\text{c}}\) filters are two well-known examples. The SBF is analogous to a fan-S\(\acute{\text{a}}\)lc\(\ddot{\text{o}}\)l\(\ddot{\text{c}}\) filter\(^{53,54}\) except for three facts: (1) the birefringence axis is continuously rotating in SBF, whereas discrete birefringent plates have discrete rotation angles in a fan-S\(\acute{\text{a}}\)lc\(\ddot{\text{o}}\)l\(\ddot{\text{c}}\) filter; (2) the overall rotation angle in SBF is not limited to \(\pi/2\) and is in fact many orders of magnitude larger; (3) there are no polarizers in SBF as in the S\(\acute{\text{a}}\)lc\(\ddot{\text{o}}\)l filter. It is this last point that warrants further discussion. In our demonstration, instead of polarizers (which, in essence, introduce polarization-dependent loss) we have Brillouin gain, which introduces polarization-dependent gain. This is a crucial distinction and is the reason why we can achieve such a narrow spectral feature. In fact, it can be shown that when the same length of the SBF (that is, the same amount of polarization rotation) is placed in between two polarizers, the resulting S\(\acute{\text{a}}\)lc\(\ddot{\text{o}}\)l filter feature is on the order of tens of gigahertz (see Supplementary Fig. 5). So why are we able to obtain sub-megahertz features when we use polarization-dependent gain? The answer lies in the positive feedback the gain produces. Much like the linewidth narrowing when gain builds up in a lasing process and the gain narrowing in the SBS process\(^{55,56}\), the dip becomes narrower and narrower when gain increases (see Figs. 4b and 6b), resulting in a five-orders-of-magnitude narrowing of the passive filter feature (see Supplementary Fig. 5).

In a nutshell, the innovation of our method lies in the mechanism of enhancing birefringent filtering using a polarization-dependent gain to create a positive feedback. It is to our knowledge the first proposal and demonstration of such a mechanism, which can be broadly implemented using other elliptically birefringent media and gain mechanisms, and therefore can potentially lead to a paradigm shift in the pursuit of ultra-narrow spectral features and their applications.

For example, the strong polarization pulling effect of SBS in the vicinity of the spectral dip leads to a high dispersion within the narrow spectral region, which can be used for realizing group delays and information storage applications (see Supplementary Fig. 1 for the theoretical predictions of the phase response and the delay response associated with the spectral dip). Another application can be a narrow-band tunable spectral filter or microwave photonic filter, which could be designed by combining the spectral dip in the gain medium with a broadband attenuator. Furthermore, the high sensitivity of the spectral dip to polarization variations can be exploited for high-precision sensing of current, stress and temperature.

Although the high sensitivity of the spectral dip to input polarization variations can enable ultrahigh sensitive measurements, it can be a drawback for some other applications, as well. For example, it is necessary to precisely align the signal and pump polarizations to the polarization eigenmodes of SBF to generate the spectral dip. We have also shown in Figs. 4b and 6b that there is a limited range of gain for which this dip can be obtained. The dip will disappear for very high or very low gain. This can lead to performance limitations in some of the above-mentioned applications. Furthermore, the maximum depth of the spectral dip in our experiments is limited to ~14 dB due to our fibre BTR and input parameters. A higher dip depth can be achieved by choosing optimal input powers and an SBF with optimal BTR of 1 (see Supplementary Fig. 8, in which a simulation shows that a dip depth of 37 dB can be obtained for an optimal BTR of 1, \(P_{\text{pump}}\) of 14.75 dBm and \(P_{\text{sig}}\) of ~35 dBm).

Other SBS-based approaches such as ref. \(^{53}\) offer an extinction ratio of 20–40 dB.

In summary, we have demonstrated a resonator-free approach of generating a sub-megahertz tunable spectral dip at room-temperature by exploiting polarization pulling in a medium with frequency-dependent polarization eigenmodes. As a specific realization, we have experimentally demonstrated a 0.72 MHz spectral dip in the Brillouin gain spectrum of a commercial spun fibre. The observed dip linewidth of 0.72 MHz is equivalent to a Q-factor of ~267 million if a resonator were used. The linewidth, depth and the location of the dip can be tuned on demand by controlling the pump frequency, the pump power and the input polarization of the signal. Moreover, with an optimal spin birefringent fibre, the dip linewidth is predicted to be as low as \(\lesssim 0.1\) MHz, corresponding to a Q-factor of two billion.

Although the current analysis of this spectral dip is carried out in fibre, this ultra-narrow feature can potentially be realized in integrated waveguides, using, for instance, chiral birefringent material or a helical waveguide. The gain mechanism is also not limited to SBS, and one can make use of polarization-dependent gain such as Raman gain or parametric gain. The essential elements required to realize such narrow spectral dips are a polarization-dependent gain and a rotating birefringence with frequency-dependent polarization eigenmodes.

The simplicity in the implementation of this technique, as well as the ultra-narrow spectral feature and the easily attainable tunability of the dip, may open a wide range of potential applications, such as ultrahigh resolution optical sensing, ultra-narrow-band tunable optical filters for microwave photonics, fast light and information storage applications.

Online content
Any methods, additional references, Nature Research reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41566-022-01015-w.

Received: 12 April 2021; Accepted: 25 April 2022; Published online: 9 June 2022

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Data availability
The data that have been used to produce the results reported in this manuscript and supplementary file are available in an open-access data repository (ref. 55).

Code availability
The codes used for the simulations are available from the corresponding authors on reasonable request.

Acknowledgements
The authors gratefully acknowledge Natural Science and Engineering Research Council (NSERC) (RGPIN-2019-07019, RGPAS-2019-00113, and CREATE 484907-16 to L.Q.), Canada Foundation for Innovation (CFI) (Innovation Fund 33415, Leaders Opportunity Fund 203429 and New Opportunities Fund 9650 to L.Q.) for funding this research. Y.L. acknowledges financial support from International Postdoctoral Exchange Fellowship sponsored by the China Postdoctoral Council and Wuhan University of Technology.

Author contributions
L.Q. supervised the project. N.C. formulated and coded the theoretical framework, performed the calculations and data analysis, and together with L.Q. determined the underlying mechanism and significance of the dip. L.Q. conceived and designed the experiment. R.G. made the first experimental observation of the spectral dip. Y.L. improved the experimental data acquisition and along with R.G. showed the tunability of the dip, experimentally. N.C. and L.Q. experimentally determined that homogeneous gain broadening is the dominant broadening mechanism. N.C. and L.Q. wrote the paper and revised it.

Competing interests
The authors declare no competing interests.

Additional information
Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s41566-022-01015-w.

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Peer review information Nature Photonics thanks Gustavo Wiederhecker, Thibaut Sylvestre and the other, anonymous, reviewer(s) for their contribution to the peer review of this work.

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