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Analogue of electromagnetically induced absorption in the microwave domain using stimulated Brillouin scattering

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Electromagnetically induced transparency/absorption (EIT/EIA) tailor the amplitude and phase response of an absorption resonance to create large dispersion, which has been exploited for applications in slow- and fast-light, and quantum information science. Since EIA enhances (induces) absorption of an already existing absorption (transmission) profile, it leads to a significant reduction in output signal power. Induction of a narrow absorption feature within a gain resonance can compensate for the signal loss while creating large dispersion at the EIA feature frequency. However, the demonstration of an analogue of EIA exploiting gain resonances has remained elusive. Here, we exploit coherent interaction between the Brillouin gain resonances in orthogonal polarization states to demonstrate controlled excitation of an analogue of EIA over microwave frequency range of 2.5–43 GHz. We induce a narrow absorption feature (~6 MHz), with controllable depth and frequency, within Brillouin gain resonance, demonstrating a novel technique for microwave photonic processing.

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The phenomenon of electromagnetically induced transparency (EIT), where a transmission window is induced in an otherwise absorption resonance, arises from the destructive quantum interference of different excitation pathways¹. The reduced absorption is accompanied by a large dispersion at the transmission frequency. Recently, electromagnetically induced absorption (EIA)², which is the counter phenomenon of invoking constructive interference between multiple interaction pathways to enhance/induce absorption, has been proposed and observed in atomic systems^{3–10}, structural resonators^{11,12}, plasmonic^{13,14}, metamaterial^{15,16}, and opto-electro-mechanical systems^{12,17–19}. Similar to EIT, modification of the amplitude spectral response in EIA accompanies dispersion tuning²⁰. EIT and its analog have been demonstrated in a variety of platforms such as atomic¹, plasmonic²¹, opto-mechanical systems^{18,22}, metamaterials²³, and photonic-chip²⁴ at optical, terahertz, and microwave frequencies. Demonstrations of EIT in these platforms have enabled applications such as slow light^{25,26}, non-reciprocal light storage and control^{27,28}, and microwave photonic delay and switching^{29–31}.

However, in the case of EIA, limited applicability results from the fact that the enhanced/induced absorption reduces the signal power below the signal level in the absence of EIA, which further reduces the measurable signal power. Recently, an analog of EIA was exploited in a plasmonic structure at a low temperature of 20 K for demonstrating Faraday rotation³². Even for the EIT, it is practically difficult to make the induced transmission equal to the signal loss induced by the absorption resonance. Therefore, the output signal power in EIT is typically lower than the input signal and complete transparency is difficult to achieve²⁵. It is, therefore, important to realize controlled excitation of narrow EIA features within a gain resonance such that the loss, which occurs in the conventional EIA and EIT process, is offset by the gain while still providing access to a large dispersion. If the absorption induced within the gain resonance is less than or equal to the amplification factor then we achieve large dispersion centered at the EIA feature frequency, which can be used for slow- and fast-light and phase shifting. However, if the depth of the EIA feature within the gain resonance is much larger than the amplification factor, then we can use EIA for realizing narrow bandwidth band-reject filters.

Real-world applications will further benefit from the excitation of gain enhanced EIA-like features in a platform that enables integration with existing photonic systems and allows optical and electrical control of the absorption feature depth and frequency over a wide frequency range. However, realization of an analog of EIA, which satisfy all the above-mentioned criteria, viz (i) EIA within a gain resonance, (ii) wideband operation within a given frequency regime, e.g. optical, terahertz, microwave (iii) access to dynamic control of EIA-like feature depth and frequency, and (iv) excitation in a waveguide platform that provides ease of integration with the existing photonic systems, is challenging.

Here we present the demonstration of an analog of electromagnetically induced absorption in the microwave domain by creating a controlled reduction of transmission (20–40 dB) in a narrow spectral window (~6 MHz) within a homogeneously broadened (36 MHz) gain resonance. We exploit the nonlinear optical process of backward stimulated Brillouin scattering (SBS) to realize the gain resonance in the microwave domain and create an analog of EIA within it.

Results

Concept of the analog of EIA in RF domain. Figure 1 shows the concept of an analog of electromagnetically induced absorption in the microwave domain using backward SBS. We generate the optical probe using the intensity modulation of an optical carrier (ω_c) from a laser diode (LD) with an radio frequency (RF) signal

of frequency Ω_{RF} . The modulated signal consists of a carrier (ω_c), and the upper and lower sidebands (USB, LSB) at frequencies $\omega_c + \Omega_{\text{RF}}$ and $\omega_c - \Omega_{\text{RF}}$, respectively (see Fig. 1a). Optical filtering of one of the modulation sidebands, $\omega_c - \Omega_{\text{RF}}$ in Fig. 1a, using a narrow band optical filter, creates a probe having optical frequencies ω_c and $\omega_c + \Omega_{\text{RF}}$.

In a backward SBS medium, the Brillouin shift $\Omega_B = 2\pi\nu_B$ for a pump of wavelength λ_p (frequency ω_p) is given as $\nu_B = \frac{2nV_a}{\lambda_p}$, where n is the refractive index of the optical mode at λ_p and V_a is the acoustic speed. A pump of frequency ω_p then creates gain and loss resonances at frequencies $\omega_s = \omega_p - \Omega_B$ and $\omega_{\text{as}} = \omega_p + \Omega_B$, respectively. The frequencies ω_s and ω_{as} are called the Stokes and anti-Stokes frequencies, respectively. The Brillouin gain (absorption) resonance has an associated phase response, whose slope depends on the Brillouin pump power and thus on the Brillouin gain and loss. The pump power-dependent Brillouin phase response finds use in slow- and fast-light^{33–35} and control of the phase matching condition in four-wave mixing³⁶.

For an arbitrary pump polarization, the pump powers along the orthogonally polarized components (x and y) depend on the input polarization state of the pump. The x - and y -polarized pump components have the Brillouin shifts of Ω_{Bx} and Ω_{By} depending on the refractive indices n_x and n_y , respectively, along the two polarization axes. In our experiments, we tune the frequency Ω_{RF} such that the modulation sideband of the probe (Fig. 1b) experiences Brillouin gain on counterpropagation to the pump (ω_p). For an arbitrarily polarized probe, the x - and y -components of the modulation sideband interact with respective pump polarization components^{37–39} to create Lorentzian gain profiles at the Stokes frequencies $\omega_{sx} = \omega_c + \Omega_{\text{RF}x}$ and $\omega_{sy} = \omega_c + \Omega_{\text{RF}y}$. Here $\Omega_{\text{RF}x}$ and $\Omega_{\text{RF}y}$ are the values of Ω_{RF} for which $\omega_p - \omega_{sx} = \omega_p - (\omega_c + \Omega_{\text{RF}x}) = \Omega_{Bx}$ and $\omega_p - \omega_{sy} = \omega_p - (\omega_c + \Omega_{\text{RF}y}) = \Omega_{By}$. We use a single-mode fiber (SMF) as the Brillouin medium for which $\frac{\Omega_{Bx} - \Omega_{By}}{2\pi} \sim 100$ kHz, where $\frac{\Omega_{Bx}}{2\pi}$ and $\frac{\Omega_{By}}{2\pi}$ are ~ 11 GHz. The small difference in the Brillouin shifts for the two polarizations occur due to the small birefringence ($\Delta n \sim 10^{-6}$) of the SMF. Due to the small difference between Ω_{Bx} and Ω_{By} , the Stokes frequencies ω_{sx} and ω_{sy} are nearly the same and gain resonances for the two orthogonal polarizations nearly overlap (see Fig. 1c). Since the phase slope for a Brillouin gain resonance depends on the pump power, Stokes polarization component with larger gain (solid red, Fig. 1c) has the large phase slope.

After counterpropagation to the pump in the SBS medium, the probe consists of x - and y -polarized carrier components E_{cx} and E_{cy} , respectively, and Brillouin gain processed Stokes components E_{sx} and E_{sy} , respectively. In the optical domain, the output intensity $I_{\text{optical}} = |E_{sx} + E_{sy}|^2 = |E_{sx}|^2 + |E_{sy}|^2$ of the Brillouin gain resonance results from the two Lorentzian gain profiles centered at ω_{sx} and ω_{sy} (see Fig. 1c). The Brillouin gain, therefore, consists of the sum of two optical intensities, which do not carry any phase information and thus no interference occurs.

Photodetection of the probe, consisting of a carrier and SBS gain processed modulation sideband, followed by S_{21} measurement on a vector network analyser (VNA) results in the RF power $S_{\text{RF}}(\Omega_{\text{RF}}) = |E_{cx}E_{sx} + E_{cy}E_{sy}|^2 = |E_{cx}E_{sx}|^2 + |E_{cy}E_{sy}|^2 + 2E_{cx}E_{sx}E_{cy}^*E_{sy}^*$ (see Supplementary Note 1). The phases and amplitudes of the Brillouin gain along the orthogonal polarizations gets transferred to the RF signals, which are generated by beating of the x - and y -polarized carrier with the x - and y -polarized gain processed modulation sidebands, respectively. The gain experienced by the probe polarization components along the x - and y -axis depends on the pump power along the respective axis^{38,39}. Besides the SBS induced optical phase (ϕ_{SBS}), the intensity modulator introduces a bias voltage dependent phase shift (ϕ_{mod} ,

Fig. 1 Concept of analog of electromagnetically induced absorption (EIA) in microwave domain. **a** Optical probe creation through modulation of light of frequency (ω_c) from a laser diode. Intensity modulation using a radio frequency (RF) signal (Ω_{RF}) is followed by a narrow band optical filter to suppress one of the modulation sidebands. **b** The optical probe consisting of the x- and y-polarized components of the laser carrier and modulation side band is let to counter-propagate to the Brillouin pump (ω_p), which is obtained from the same laser diode, inside the stimulated Brillouin scattering (SBS) medium. **c** Schematic of the SBS induced optical gain and phase responses corresponding to the Stokes components of orthogonal polarizations. **d** RF amplitude (P_{RF} (dB)) and phase response, as a function of the radio frequency f_{RF} , of the orthogonally polarized probes after downconversion in the photodetector and S_{21} measurement. The RF phase (ϕ) is a combination of the Brillouin phase (ϕ_{SBS}) and modulator bias-dependent phase shift ϕ_{mod} . **e** Coherent interaction between the orthogonally polarized probe components give rise to EIA-like feature in the RF domain.

Fig. 1d)^{40,41}, which is different for the orthogonally polarized probe components (Supplementary Fig. 1). The combined effect of ϕ_{mod} and ϕ_{SBS} is to shift the RF phases, corresponding to the x - and y -polarizations, along the phase (ϕ) axis (see Fig. 1d). By adjusting the pump polarization (Fig. 1b), we achieve larger gain for the Stokes polarization component with lower power and smaller gain for the Stokes polarization component of higher power such that the RF powers of the x - and y -polarized components are equalized at the EIA-like feature frequency (P_{RF} , Fig. 1d). The combined effect of ϕ_{mod} and ϕ_{SBS} then results in RF phases (ϕ) of the x - (red solid) and y -polarized (green dashed) gain resonances to differ by $\sim \pi$ at the frequency (see vertical line in ϕ , Fig. 1d) for which the RF amplitudes of the x - and y -polarized Brillouin gain are equal (P_{RF} , Fig. 1d), which causes destructive interference. The destructive interference then introduces a large reduction in transmission within the Brillouin gain profile in the RF domain (see Fig. 1e). The coupling between the RF phases and amplitudes of two orthogonally polarized gain resonances, therefore, results in induced absorption. Coupling between the amplitude and phase response of different resonances has been exploited in a variety of photonic systems to demonstrate analogs of coherent interactions, e.g. Fano resonance, EIT³ over frequency regimes ranging from optical, THz to microwave.

Recently, an analog of EIT was demonstrated where the interference between two anti-Stokes Brillouin excitations was used to induce transparency in an absorption resonance^{27,28}. In ref. ³², interference between a plasmon oscillation and a waveguide resonance was used to demonstrate an analog of EIA. In our demonstration, the transmission reduction within the gain profile occurs due to an interference between two orthogonally polarized gain resonances. It is therefore equivalent to an analog of EIA and is different from the spectral hole burning, which occurs in optical domain due to the pump depletion and gain saturation^{42–44}.

The large reduction in transmission within the gain resonance introduces a sharp dispersion centered at the induced absorption

frequency. Using the large dispersion slope, we obtain slow- and fast-light with an absolute resonant delay of more than a μs at the EIA-like feature frequency, which is much larger than the delay obtained using the conventional Brillouin gain for the same pump power. Recently, slow- and fast-light of microwave signals was achieved in superconducting nano electromechanical circuits exploiting EIT and using microwave control field²⁹. We harness the optical and electrical control of the induced absorption feature through backward SBS and modulator bias, respectively, to achieve negative to positive delay tuning and photonic switching of microwave signals at room temperature, which has the potential for enabling microwave photonic signal processing applications. Since the SBS process acts as an optical filter that provides control over the amplitude and phase of the modulation sideband, our approach of creating an EIA analog should be realizable with any type of optical filter or gain resonance with complex transfer function.

Controlled excitation of the EIA-like resonance. Figure 2a shows the experimental setup used for demonstrating the analog of EIA using backward SBS. We split a 1550 nm continuous-wave signal from a narrow linewidth ($\Delta\nu_{\text{FWHM}} < 5$ kHz) laser (Teraxion Inc.) into two arms using a fiber beam splitter. Here $\Delta\nu_{\text{FWHM}}$ is the full-width at half-maximum bandwidth of the LD. In the probe arm, we use a z -cut intensity modulator (IM: Thorlabs) with a 3 dB bandwidth of 35 GHz to modulate the laser carrier (ω_c). We use the RF signal (Ω_{RF}) from a 43 GHz Vector Network Analyser (Keysight model: PNA N5224A) to drive the IM with RF signal powers in the range of 15–18 dBm. To control the bias voltage of the IM, we use a direct current power supply. The modulated signal is amplified using a low-noise erbium-doped fiber amplifier (Pritel) followed by filtering of one of the modulation sidebands using a fiber Bragg grating (FBG: AOS make) with a 3 dB bandwidth < 5 GHz. This results in an optical probe containing only a laser carrier and a single modulation sideband (Fig. 2a).

Fig. 2 Experimental setup and occurrence of the analog of electromagnetically induced absorption (EIA). **a** Experimental setup for realizing the analog of EIA resonance using backward-stimulated Brillouin scattering (SBS) at the Brillouin shift (Ω_B). Normalized radio frequency (RF) amplitude P_{norm} (dB) (solid black) and phase (red dashed) profile **b** when the pump and probe polarizations were aligned to maximize the gain at a bias of 1.360 V, **c** when the polarizations of the pump and probe are adjusted at the same voltage bias as in **a**, showing a reduction of gain to 25 dB and **d** occurrence of a narrow EIA-like feature accompanied by sharp dispersion as the voltage bias is tuned to 0.520 V, while keeping other parameters the same as in **b**. LD laser diode, IM intensity modulator, DC direct current, EDFA erbium-doped fiber amplifier, PC polarization controller, VNA vector network analyser, OSA optical spectrum analyser, SMF single-mode fiber, PD photodiode.

In the pump arm, we amplify the laser carrier (ω_c) using a high-power erbium-doped fiber amplifier (Amonics: 2W) to control the pump power. For observing the induced absorption feature at the Brillouin shift (Ω_B), we tune Ω_{RF} around Ω_B in the probe arm. The pump frequency ω_p is, therefore, the same as the laser carrier frequency ω_c . The pump and the probe are launched into a 500 m long SMF using circulators C1 and C2, respectively. In the SMF, the probe counterpropagates to the pump and the modulation sideband at $\omega_c - \Omega_{RF}$ sees the Brillouin gain. The Brillouin gain experienced by the probe sideband is measured in the optical domain using an optical spectrum analyser (OSA-Anritsu). The RF gain resonance, which is generated due to the beating of the probe carrier ω_c with the Stokes modulation sideband, is measured using a high-speed photodetector (Finisar) followed by the vector network analyser. The S_{21} measurement on the vector network analyser is used to obtain the RF amplitude, phase and delay response.

For demonstrating the analog of EIA at radio frequencies (Ω_{RF}) other than Ω_B , we modulate the laser carrier ω_c in the pump arm using a phase modulator (Thorlabs). We use a 40 GHz signal generator (Agilent: E8257D) to modulate the laser in the pump arm. The modulation sideband of frequency of $\omega_c + \Omega_{RF} + \Omega_B$ acts as the pump for the probe sideband of frequency $\omega_c + \Omega_{RF}$. We filter the carrier and other modulation sideband in the pump arm. In the pump and the probe arm, we use fiber polarization controllers (PCs) to control the polarization of the pump and the probe.

For a fixed pump power, when we align the pump and probe polarizations by adjusting their respective PCs, the maximum gain occurs. Figure 2b shows the normalized RF power P_{norm} (dB) (black solid) and RF phase response (red dashed) at the Brillouin shift Ω_B , which is ~ 10.83 GHz for our SMF around 1550 nm, when the pump and probe polarizations are aligned and the IM bias voltage (V_b) is 1.36 V. A maximum gain of 40 dB appears when the pump and probe polarizations are aligned. The asymmetry in the Lorentzian profile in Fig. 2b occurs due to the gain seen by a higher order acoustic mode. As the pump and probe polarizations are misaligned while keeping the bias voltage fixed at 1.36 V, the gain drops to 25 dB (Fig. 2c). Tuning the bias voltage from 1.36 to 0.52 V then creates a large reduction (~ 37 dB) in transmission within the gain profile (Fig. 2d). This large dip in transmission occurs due to the destructive interference between the x - and y -polarized probe components as explained in Fig. 1. The tuning of the pump and probe polarizations splits the pump and probe power along the orthogonal polarizations in such a way that the probe polarization component with low (high) power sees the pump polarization component with higher (lower) power. Therefore, by adjusting the pump and probe polarizations we can equalize the RF signal amplitudes of the x - and y -polarized probes (see Fig. 1d). Tuning of V_b shifts the SBS phases (ϕ_{SBS}) seen by the x - and y -polarized probe components vertically along the phase axis (see Fig. 1d). Destructive interference occurs at the radio frequency for which the x - and y -polarized RF components have the same amplitude and a π phase shift exists between them. The induced absorption feature in Fig. 2d has a narrow 3 dB spectral width ~ 6 MHz, which is six times smaller than the bandwidth of the conventional SBS gain profile in our SMF. The induced absorption feature introduces a sharp dispersion (see red dashed in Fig. 2d), which finds potential use in tunable RF delay applications²⁹. Figure 2b–d shows that the tuning of the pump and probe polarizations in combination with V_b creates the condition for the destructive interference within the Brillouin gain profile.

Here, we show how the depth, frequency, and the number of induced absorption features within the gain resonance can be controlled. Figure 3a, b shows the experimental (solid black) and simulated (red dashed) plots, which are obtained from the model

developed in the Supplementary Note 1, for the optical control of the EIA-like feature depth. Tuning the pump power from 215 mW (Fig. 3a) to 225 mW (Fig. 3b), at a fixed V_b , increases the depth of the induced absorption from 21 to 41 dB. To explain the origin of this large increase in the absorption due to a small change in the pump power, we plot the simulated RF amplitudes and phases for the orthogonal polarizations in the Supplementary Discussion. Supplementary Fig. 2 shows the simulated RF amplitude and phases of the orthogonal polarizations corresponding to the model fits in Fig. 3a, b. From our simulations, we note that with an increase in the pump power, the difference in the RF amplitudes of the orthogonally polarized components reduces from 0.4 to 0.05 dB (Supplementary Fig. 2b, e). However, the slight increase in the pump power still maintains the phase shift between the orthogonally polarized components at π . A higher pump power in Fig. 3b, therefore, equalized the RF amplitudes of the orthogonally polarized components better, thus optimizing the destructive interference to create larger absorption. Induced absorption of 21 dB in Fig. 3a is nearly the same as the gain, which shows that we can achieve transparency by making the induced absorption equal to the amplification provided by the gain resonance. Signal gain, loss and transparency are all measured with respect to the RF signal level for the pump-off case, which is the same as the level outside the gain bandwidth and is determined by the RF insertion loss of the photonic system.

To demonstrate tuning of the induced absorption feature frequency, we tune the bias voltage at a fixed pump power. Figure 3c, d shows the experimental and simulated plots for electrical control of the induced absorption feature frequency. Varying V_b from 4.186 (Fig. 3c) to 3.582 V (Fig. 3d) switches the induced absorption feature frequency from 10.819 to 10.828 GHz, which corresponds to a change of 9 MHz in the induced absorption frequency. The physics of the induced absorption feature frequency switching can be explained using the interference between the orthogonal polarization components (Supplementary Fig. 3) corresponding to the simulation results in Fig. 3c, d. Here the RF amplitudes of the two orthogonal polarizations are nearly equal at two different frequencies (Supplementary Fig. 3b, e). Tuning of the bias voltage causes the π phase shift condition to switch between these two frequencies, as shown in Supplementary Fig. 3c, f. Electrical control of the EIA-like feature frequency using a small change in the bias voltage has the potential for high-speed, high-resolution (sub 10 MHz) photonic switching of microwave signals^{29,45–47}.

Finally, we explore the creation of induced absorption at multiple frequencies within the gain profile by controlling the polarizations of the pump and the probe, the pump power and V_b . Figure 3e, f shows the measured and simulated plots for the creation of induced absorption at one and two frequencies, respectively. Unlike electrical control where we switch the condition of destructive interference from one frequency to the other, we simultaneously create the condition for destructive interference at two frequencies in Fig. 3f. Once again, we explain these experimental results using the interference between the RF amplitudes and phases of the orthogonal polarizations (Supplementary Fig. 4) corresponding to the simulations in Fig. 3e, f. The 3 dB bandwidth of the dual frequency induced absorption in Fig. 3f is ~ 11 MHz, which makes it a potential candidate for a high-resolution microwave photonic bandpass filter.

We have demonstrated the concept and control of the induced absorption depth, frequency, and number of absorption windows using a microwave frequency Ω_{RF} equal to the Brillouin shift Ω_B for our fiber. In order to demonstrate the analog of EIA at frequencies Ω_{RF} other than Ω_B , we modulate the optical field (ω_c) in the pump arm, using an RF signal generator (Agilent:8257D),

Fig. 3 Controlled excitation of the analog of electromagnetically induced absorption (EIA). **a, b** Measured (solid black) and simulated (red dashed) optical control of the analog of the induced absorption feature depth showing that the induced loss can be made equal to or much larger than the amplification factor by varying pump power for a fixed probe power and voltage bias. **c, d** Electrical control demonstrated by switching of the induced absorption feature frequency by 9 MHz within the homogeneously broadened gain profile as the voltage bias is tuned by 0.6 V. **e, f** Excitation of multiple induced absorption features within the gain spectrum by creating the destructive interference at more than one frequency within the gain spectrum via control of bias and optical powers. Simulated results for the EIA-like resonance are obtained using the model described in Supplementary Note 1.

to obtain the Brillouin pump at $\omega_c + \Omega_{\text{RF}} + \Omega_B$ while suppressing other frequencies in the pump arm. We demonstrate induced absorption features with a minimum depth of 35 dB from 2.5 to 43 GHz, a frequency variation with a factor of 17 (Fig. 4a–f). For demonstrating induced absorption in Fig. 4a–f, we optimize the system parameters such as the pump power, V_b , and the polarizations of the pump and the probe to maximize the absorption depth within the gain resonance. Induced absorption profiles in Fig. 4a–f accompany large dispersion, which is evident from the large slope of the phase spectrum (red dashed) in these figures. In order to obtain the phase profiles shown in Fig. 4a–f, we take the difference of the probe RF phase under the pump-on and pump-off condition. The sign of the phase in Fig. 4a is different from that shown in other figures, which enables tuning of the RF delay from positive to negative values. The wideband tunability of induced absorption feature complemented with large dispersion, and control over the induced absorption frequency and depth within the gain spectrum paves the way for RF photonic signal processing⁴⁸ applications such as high-resolution two-channel RF switching, tunable RF delay and phase shifter, microwave photonic filters, and signal routing⁴⁹.

Excitation of induced absorption within EIT-like resonance.

Most of the demonstrations of EIA and its analog have relied on enhancing the loss of an existing absorption resonance. Induction of an absorption feature within an EIT-like transparency window was recently proposed using a hybrid opto-electromechanical system¹⁸ and demonstrated at THz frequencies using a three-resonator metasurface system¹², where a small absorption was induced in an EIT-like resonance. Using backward SBS, an EIT-like resonance can be created in the microwave domain exploiting a coherent interaction between the Brillouin Stokes and anti-

Stokes resonance, under the condition that $\frac{P_{\text{AS}}}{P_s} \gg 1$ (ref. 50), where P_{AS} and P_s are the input powers of the probe modulation sidebands corresponding to the anti-Stokes and Stokes frequencies before SBS processing. Figure 5a shows an EIT-like resonance in the microwave domain centered at the Brillouin frequency Ω_B . Creation of an EIT-like resonance does not require interference between the orthogonal polarization components of the interacting pathways, as needed for induced absorption within a gain resonance. In order to create an EIT-like resonance in Fig. 5a, we use a FBG to make the ratio $\frac{P_{\text{AS}}}{P_s} \gg 1$ (ref. 50). We align the pump and probe polarizations to maximize the gain and loss seen by the Stokes and anti-Stokes sidebands, respectively. Since $P_{\text{AS}} \gg P_s$, Brillouin absorption creates an inverted Lorentzian that intersects with the Brillouin gain profile at two frequencies. If the phase difference between the intersecting gain and loss resonance at the intersection frequencies, where their amplitudes are the same, is equal to π , then destructive interference between them leads to creation of two rejection bands, one on each side of the transmission window. The resulting RF spectrum has the appearance of an EIT-like resonance³⁰, as shown in Fig. 5a. The 3 dB bandwidth and depth of the rejection bands are 13 MHz and ~ 38 dB, respectively. The 3 dB bandwidth of the transparency window and depth of the rejection sidebands are optically and electrically controllable.

In order to create induced absorption within the transparency window of EIT-like resonance, we adjust the polarization of the pump and probe while keeping the V_b fixed at a value of 5.958 V used in Fig. 5a. Tuning of the pump and probe polarizations reduces the depth of rejection sidebands (Fig. 5b) because different powers get coupled along each polarization axis and the condition of destructive interference is disturbed. When the intensity modulator bias voltage is tuned from 5.958 to 6.024 V,

Fig. 4 Wideband excitation of analog of electromagnetically induced absorption (EIA). **a–f** Observation of analog of EIA from 2.5 to 43 GHz by tuning the Brillouin pump frequency. For each of the frequency, bias and other parameters were optimized to maximize the extinction. Black solid line—normalized radio frequency (RF) amplitude response (P_{norm}) (dB); red dashed line—RF phase response as a function of radio frequency f_{RF} .

Fig. 5 Concept of induced absorption within an electromagnetically induced transparency (EIT) like resonance. **a** Black solid line—normalized radio frequency (RF) amplitude response (P_{norm}) (dB) of EIT-like resonance arising from the coherent interaction of Brillouin anti-Stokes and Stokes field with a power ratio $\gg 1$; red dashed line—phase response for the EIT-like resonance in the RF domain. **b** Normalized RF amplitude response showing a narrow induced absorption feature within an EIT-like resonance. The induced absorption within the EIT-like resonance is obtained through control of the pump and probe polarizations and tuning of bias voltage at a fixed pump power. A sharp dispersion accompanies the induced absorption feature within the EIT-like resonance, as seen from the phase response.

we observe a reduction of ~ 35 dB in transmission over a narrow bandwidth of 6 MHz (Fig. 5b) within the transparency window. The induced absorption appears at the center of the transparency window, which primarily consist of the gain resonance⁵⁰, when we adjust the pump and probe polarizations and vary the bias to create the condition for destructive interference of the gain resonances corresponding to orthogonal polarizations. This induced absorption feature within a transparency window is analogous to an exotic RF filter with three ultra-high rejection bands separated by 21 MHz. Similar to EIA-like features in Fig. 3a–c, induced absorption within an EIT-like resonance is flexible to optical and electrical control and accompanies large dispersion at the frequency of induced absorption. RF phase shifts of more than 360° are observed using induced absorption within an EIT-like resonance. The tuning of the phase slope sign corresponds to RF delay tuning from positive to negative delay.

The induced absorption within the EIT-like spectrum is tunable over a wide range of frequencies using a tunable pump configuration. Here, we demonstrate excitation of induced

absorption within a transparency window over a frequency range of 2.5–43 GHz (Fig. 6). The controllability through optical and electrical means is also achievable at non-Brillouin frequencies. Tunability and control of an induced absorption feature within an EIT-like profile opens up high-resolution RF signal processing applications such as tunable RF delay, RF pulse shaping⁵¹, arbitrary waveform generation⁵², and notch filters¹⁷.

RF delay using EIA-like resonance. It is evident from our results that an induced absorption feature within the homogeneously broadened Brillouin gain profile accompanies large dispersion. We use a vector network analyzer to measure the RF phase and group delay of the probe signals. In general, SBS provides a resonance group delay (T_{gd}) that depends on the Brillouin pump power (P_p) through the gain parameter $G_b = \frac{g_b P_p L_{\text{eff}}}{A_{\text{eff}}}$ as $T_{\text{gd}} = \frac{G_b}{\Gamma_b}$, where g_b is the Brillouin gain coefficient, L_{eff} is the effective length, A_{eff} is the effective mode area, and Γ_b is the Brillouin gain bandwidth. Large pump power and thus large gain imply more

Fig. 6 Wideband excitation of analog of electromagnetically induced absorption (EIA) within a transparency window. Black solid line—normalized radio frequency (RF) amplitude response; red dashed line—phase response. **a–f** Observation of the analog of EIA within the transparency from 2.5 to 43 GHz by tuning the Brillouin pump frequency. For each of the frequency, bias and other parameters were optimized to achieve the large extinction.

resonance delay. However, gain saturation⁵³, pump depletion effects, and pulse distortion^{54,55}, which occur at high pump powers, limit the maximum gain, which restricts the maximum delay to a few tens-of-nanoseconds. A number of Brillouin-based delay schemes have already been demonstrated^{27,33–35,56–58}. In ref. ²⁷, a delay of 110 μ s was achieved by induction of a narrow transparency window (~ 17 kHz) in a microsphere resonance using forward SBS. We exploit backward SBS in a linear waveguide to induce a narrow absorption feature (~ 6 – 8 MHz) within a gain profile and achieve resonant RF group delay of up to a μ s, which is nearly 30 times larger than the RF delay introduced due to a typical Brillouin gain resonance using the same pump power. Such large resonant delays enable wide delay tunability without introducing much pulse distortion as long as the pulse bandwidth is smaller than the delay medium bandwidth^{33,34,53}. By controlling the polarizations of the pump and probe, modulator bias voltage, and the pump power, the delay can be tuned from negative to positive at a given microwave frequency.

Figure 7a shows the measured Lorentzian gain profile of Fig. 2b for the condition when both the pump and probe polarizations are aligned and the related RF delay is shown in Fig. 7b. Even with a large gain of 40 dB, the observed RF group delay at the Brillouin shift is only ~ 40 ns. For the same pump power as in Fig. 7a, b, tuning the pump and probe polarization and intensity modulator bias voltage results in creation of a narrow band absorption (Fig. 7c) feature within the Brillouin gain profile. While the polarization adjustment reduces the gain to 25 dB in Fig. 7c, large dispersion at the induced absorption feature frequency introduces a large absolute delay of about 1 μ s (Fig. 7d).

Using the tunable pump configuration, described earlier for wideband demonstration of induced absorption, we demonstrate RF delay and delay tuning from negative to positive value at non-Brillouin frequencies. Figure 8a, b shows the measured RF response and group delay, respectively, at a frequency of 17 GHz using induced absorption within an EIT-like resonance. By varying the bias and polarization conditions, we modify the RF amplitude and phase response of Fig. 8a to obtain the RF response in Fig. 8c. Figure 8d shows the RF delay response corresponding to the RF response shown in Fig. 8c. We, therefore,

demonstrate the possibility of tuning the group delay from a negative (-800 ns) to positive (800 ns) value at a fixed frequency, as shown in Fig. 8b, d, by varying the bias and polarization conditions. The group delay tuning is verified by the change in the direction of the phase spectra slope (Fig. 8a, c). Such significantly large delay tunability over a wide frequency range is of importance in applications such as RF delay lines⁵⁹ and buffers. The dispersion in this process can be tuned by adjusting the parameters such as input optical powers, applied voltage bias, and the power ratio between the polarization components to obtain large RF delay tunability in comparison with that obtained using just the SBS process. With the advent of on-chip SBS^{60–67}, silicon intensity modulators⁶⁸, and other chip-scale components, integrated circuits can be developed for realizing the analog of EIA for microwave photonic applications.

Discussion

Most of the EIA demonstrations, reported so far, are based on enhancing the absorption of an existing absorption resonance. EIA through induction of absorption in a transmission profile was recently proposed¹⁸ and demonstrated at a fixed THz frequency¹². In all these demonstrations, enhancement or induction of absorption reduces the signal power below the level before the EIA feature was created. In this work, we exploit coherent interaction between the orthogonal polarization components of a probe, which consists of a laser carrier and a single modulation sideband, to create narrow band absorption features within a homogeneously broadened Brillouin gain profile in the microwave domain. The amplification provided by the gain resonance offsets the signal loss due to induced absorption while still providing large dispersion. Since EIA can occur due to the enhancement of existing absorption or induction of absorption in a transmission or gain profile, we characterize EIA using the following two definitions:

$$IF = \frac{T_{EIA}(\omega_o)}{T_{max}}, \quad (1)$$

$$EF = \frac{A_{EIA}(\omega_o)}{A(\omega_o)}, \quad (2)$$

Fig. 7 Radio frequency (RF) group delay measurement at the Brillouin frequency. **a** Normalized RF amplitude response (P_{norm} (dB)) when the pump and probe polarization are aligned. A maximum gain of 40 dB is observed for this condition. **b** RF group delay corresponding to **a** showing a small delay of ~40 ns. **c** Normalized RF amplitude response when the polarization is adjusted and the voltage bias is tuned to obtain the absorption window. **d** RF group delay response corresponding to the induced absorption feature demonstrating that steep dispersion at the induced absorption feature frequency results in a large group delay of ~1 μs using the same Brillouin pump power.

Fig. 8 Radio frequency (RF) group delay tuning. **a** Normalized RF amplitude (P_{norm} (dB)) response (solid black) and phase response (dashed red) for an initial gain of about 40 dB. **b** RF group delay corresponding to RF response in **a**. **c** Tuning the bias voltage and polarizations modify the RF amplitude and phase response. **d** Measured RF group delay corresponding to the RF response in **c**. Tuning of the RF phase slope in **a**, **c** results in delay tuning from a negative to positive value (**b**, **d**). Insets in **b** and **d** show a zoomed-in section of the RF delay spectrum.

where IF is the induction factor, ω_0 is the resonance frequency of the EIA feature, $T_{\text{EIA}}(\omega_0)$ is the transmission at ω_0 when induced absorption occurs, T^{max} is the maximum transmission of the transparency window or gain profile containing the induced absorption feature, EF is the absorption enhancement factor (EF), $A_{\text{EIA}}(\omega_0)$ is the absorption at ω_0 when induced absorption occurs, and $A(\omega_0)$ is the absorption at ω_0 in the absence of absorption enhancement. The EF therefore refers to an increase in absorption in the presence of EIA compared to the absorption when EIA was absent and is consistent with the definition used to quantify EIA in literature².

Table 1 shows a comparison of the absorption EF and IF achieved in different EIA systems. Each entry in the table is labeled using EF or IF to highlight the fact that if the EIA is due to

enhancement of absorption or due to induction of absorption in a transparency or gain. For the entries in Table 1, we use the values given in literature or calculated¹⁹ them, wherever they were not given, from the data shown in the corresponding references using the definition for IF or EF. The EF in many of these systems is <10. We use coherent Brillouin interactions to induce controlled reduction of transmission in the range of 20–40 dB (Fig. 3a, b) in a narrow spectral window (~6 MHz) within a Brillouin gain resonance. In our case, 40 dB of induced absorption correspond to an IF of 10,000.

Dynamic control of the induced absorption feature depth and frequency, using optical and electrical tuning of the amplitude and phase of the interfering gain resonances, has the potential to enable RF applications such as RF switching, tunable RF delay,

Table 1 A comparison of absorption enhancement in different systems.

System/method	Enhancement factor (EF) or inducement factor (IF)	Regime	Tuning
This work	10,000 (IF)	Microwave (2.5–43 GHz)	Electrical, optical, and frequency
Rb-85 in a vapor cell ²	1.7 (EF)	Optical	–
Three-resonator metasurface ¹²	0.78 (IF)	Terahertz	–
Coupled plasmonic osillators ¹³	1.35 (EF)	Terahertz	–
Coupled WGMs ¹⁹	2 (EF)	Optical	–

and filtering. Narrow absorption features within an EIT-like resonance may find application in RF pulse shaping and simultaneous filtering of multiple signals. The SBS process in itself offers an edge to this technique where the central frequency of operation, bandwidth, and profile can be tuned using the input Brillouin pump parameters. The demonstration of controllable induced absorption in a fiber-optic platform using off-the-shelf components enables integration with existing fiber-based microwave photonic systems. Recent demonstrations of SBS in chalco-genide and silicon platforms along with on-chip silicon modulators, gratings, and lasers^{64,65} will enable integrated RF signal processing applications^{69,70} based on coherent Brillouin interactions. Since SBS provides optically tunable amplitude and phase response, this approach can be used with any gain medium with complex gain response.

Data availability

All the experimental and simulated data are available in this paper. For more technical information, we provide the relevant data in the Supplementary Information. Further supporting information could be provided by the corresponding author upon reasonable request.

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Author contributions

R.P. conceived and developed the idea. R.P. and S.S.A. designed the experiments. S.S.A. and A.B.Y. made experimental setup and conducted measurements. R.P. and S.S.A. analyzed the results and wrote the manuscript. R.P. supervised the project.

Competing interests

The authors declare no competing interests.

Additional information

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