Abstract—We propose a novel scheme for slow light based on a resonant three-level lambda system (RTLS) in a p-doped semiconductor heterostructure. Numerical simulations show that a slow-down factor of 145 and a slow-down-bandwidth product exceeding 200 THz can be achieved in semiconductor quantum wells at room temperature. These figures of merit make the RTLS slow light especially useful for the enhancement of the optical nonlinearity in high bandwidth all-optical signal processing applications.

Index Terms—All-optical signal processing, semiconductor heterostructures, slow light.

I. INTRODUCTION

SLOW LIGHT has many potential engineering and scientific applications [1]. To date, considerable research efforts for slow light have been centered on establishing a tunable optical delay line, i.e., an optical buffer [2]. The optical buffer is a linear optical device in which the steep change of the refractive index versus the optical wavelength leads to a drastic change of the refractive index of the waveguide; therefore a slow-down-bandwidth product, these devices are not suitable for the enhancement of nonlinear optical processes. For a nonlinear slow light device to be able to handle an ultrafast optical signal with a bit rate > 100 Gbit/s, the slow-down factor needs to be $\gg 1$ and the slow-down-bandwidth product needs to be $\gg 1$ THz.

Here, we propose a novel gain-assisted slow light mechanism based on a resonant three-level lambda ($\Lambda$) system (RTLS) in a p-doped semiconductor heterostructure. We have designed an RTLS slow light device based on semiconductor quantum wells. We show that the resulting slow-down factor and the slow-down-bandwidth product can exceed 145 and 200 THz, respectively. The maximum bandwidth of the RTLS slow light device is essentially limited by the ultrafast excitonic dephasing in semiconductors which is on the order of THz at room temperature.
temperature. The organization of this paper is as follows. In
Section II, we will discuss in detail the mechanism of the RTLS
in a p-doped semiconductor heterostructure, its relationship
to slow light, and its implementation using semiconductor
quantum wells. In Section III, we will systematically study
the dependence of slow light performance on several material
parameters. For completeness, we will also discuss conditions
for superluminal light using RTLS. The limitations of RTLS
and their potential solutions will be discussed in Section IV.

II. RESONANT THREE-LEVEL A SYSTEMS IN P-DOPED
SEMICONDUCTOR HETEROSTRUCTURES

A. Slow Light via an RTLS

For a general three-level SRS system as illustrated in
Fig. 1(a), optical gain for the signal beam can be created when
both pump and signal beams satisfy a two-photon resonance
condition, i.e., \( \delta_2 = (\omega_p - \omega_{2g}) = (\omega_s - \omega_{2g}) = 0 \) in the case
of a large pump detuning \( \delta_p = \omega_p - \omega_{2g} \). Because of the large
pump detuning, the slow-down factor achievable from the
SRS configuration is small. One possible way to increase the
slow-down factor is to reduce the pump detuning such that
both the pump and the signal are nearly in resonance
with the transition from \[ \left| 1 \right> \] to \[ \left| 2 \right> \] as illustrated in Fig. 1(b).
In the following, we will refer to the resonant three-level A
systems in Fig. 1(b) as a resonant RTLS. For comparison, an
electromagnetic induced transparency (EIT) configuration in
the same three-level system is also shown in Fig. 1(c). Despite
a seemingly similarity between RTLS and EIT, the underlying
mechanism for slow light in these two systems is very different.
In EIT, the slow light is the result of the cancelation of signal
absorption due to the coherence of the dipole-forbidden transition
between \[ \left| 1 \right> \] and \[ 0 \]. Because of the fast decoherence between \[ 0 \]
and \[ 1 \] in most of the semiconductor materials, it is very difficult to experimentally observe EIT at room tempera-
ture [20], [21]. In contrast, the slow light in RTLS depends only
weakly on the coherence between \[ 0 \] and \[ 1 \] as will be shown
in the following.

The signal gain in RTLS required for slowing down the signal
beam can be achieved by establishing the population inversion
between \[ \left| 1 \right> \] and \[ \left| 2 \right> \]. In the presence of a strong pump beam, the
population will be transferred from \[ 0 \] to \[ 1 \] via an intermediate
level [2]. We must quickly deplete the population in \[ 1 \] such that
a population inversion between \[ 1 \] and \[ 2 \] can be established.
The above condition can be satisfied if the carrier relaxation rate
between \[ 2 \] and \[ 1 \] and \[ 1 \] and \[ 0 \], \( \Gamma_{21} \) is much slower than that between \[ 1 \] and \[ 0 \]. Note the mechanism to achieve the gain in the
RTLS is different from that in a typical three-level laser system
[22]. In the latter case, \( \Gamma_{21} \gg \Gamma_{30} \) and the population inversion
is established between \[ 0 \] and \[ 1 \].

In semiconductor heterostructures (e.g., QWs), the intersub-
band relaxation time can be as short as 200 fs [23]. This is much
shorter than the interband carrier recombination time which is
typically on the order of 1 ns; therefore one possible implement-
ation for RTLS in semiconductor heterostructures is sug-
gested in Fig. 1(b). The band structure of a typical QW near
the band edge consists of one doubly degenerate conduction
band and two doubly degenerate valence bands: the heavy-hole
(HH) and the light-hole (LH). The explicit implementation of
RTLS in such a three-level system is described in the following.
The left-hand circularly polarized pump beam \( (\sigma_-) \) is coupled
to the transition between LH \( \downarrow \) and C \( \uparrow \), where \( \uparrow \) denotes the
spin-up state and \( \downarrow \) denotes the spin down state. The right-hand
circularly polarized signal beam \( (\sigma_-) \) is coupled to the transi-
tion between HH \( \uparrow \) and C \( \uparrow \). The separation between the HH and
the LH should be made larger than the phonon energy such that
even at the room temperature, the LH state can be made
a true ground state by a proper p-type doping. For example, in
a GaAs/AlAs QW, the separation between the HH and the LH
can be as large as 55.2 meV when the well width is 1.5 nm. It
is worthwhile to mention that the other half of the degenerate
three-level system which consists of LH \( \downarrow \), HH \( \uparrow \), and C \( \downarrow \) will
not couple to the pump and signal beams because of the optical
selection rule and large off resonances from both the pump and
signal beams. These uncoupled states (LH \( \uparrow \), HH \( \downarrow \), and C \( \downarrow \)),
however, can modify the carrier relaxation rates. For example,
the effective carrier density in C \( \uparrow \) can be only half of the total
physical carrier density in the conduction band because half of
the carriers can be moved to C \( \downarrow \) if the spin flip time is shorter
than the carrier relaxation time between the conduction band
and the valence band. Rigorously speaking, we will also need
to take into account the relaxation from HH \( \downarrow \) to LH \( \downarrow \) and HH
\( \downarrow \) to LH \( \uparrow \) to LH \( \downarrow \) in order to determine the effective \( \Gamma_{30} \). The

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**Fig. 1.** (a) Energy-level diagram for the conventional stimulated Raman scattering (SRS). (b) Energy-level diagram for the resonance three-level \( A \) system (RTLS) in a direct-bandgap zinc-blend semiconductor quantum heterostructure such as quantum well, \( \delta_p \) and \( \delta_2 \) are the pump detuning and the pump-signal detuning, respectively. (c) Energy-level diagram for an electromagnetically induced transparency (EIT) system in the same quantum well.
most notable impact from the un-coupled states is that higher pump intensity may be required. Changes to other parameters are expected to be within an order of magnitude.

At room temperature, the typical carrier recombination time between the conduction band and the valence band of a QW is on the order of 1 ns. But as mentioned above the typical inter-subband relaxation time can be as short as 200 fs. Therefore, the carrier relaxation between the HH and LH is much faster than that from the conduction band to the HH band. In the presence of a strong pump beam, the population inversion can be established between C ↑ and HH ↑ if a proper p-type doping level exists such that the LH can be made as the ground state and the HH can be initially depleted of electrons without any coupling to external light. This creates optical gain for the signal beam. From the Kramers–Krönig relation, the gain experienced by the signal beam corresponds to a reduction of its group velocity, i.e., slow light. In the following we will show that the operating bandwidth of the RTLS slow light system, i.e., the bandwidth within which the slow-down factor remains nearly a constant, is determined by the fast excitonic dephasing rate between [2] and [1] which is on the order of THz in semiconductor QWs. This, in contrast to the SOA slow light mechanism where the operating bandwidth is limited by a slow carrier combination rate, allows the RTLS system to be more suitable for ultra high speed applications.

To analyze the slow light in the RTLS system as shown in Fig. 1(b), we use the density matrix method and deduce the slow-down factor from a time-dependent optical dielectric constant that is experienced by the signal beam. Because the inhomogeneous broadening of the state-of-the-art QWs is small compared to the homogeneous broadening [24], the inhomogeneous broadening will be ignored in the following calculations. The evolution of the density matrix follows the Liouville equation as follows:

\[
\dot{\rho}_{00} = -\gamma_{00}\rho_{00} + \Gamma_{10}\rho_{11} + \Gamma_{20}\rho_{22} - \mathcal{I}\rho_{02} + \mathcal{I}\rho_{20}
\]

\[
\dot{\rho}_{11} = -\gamma_{11}\rho_{11} + \Gamma_{21}\rho_{22} - \mathcal{I}\rho_{10} - \mathcal{I}\rho_{01}
\]

\[
\dot{\rho}_{22} = -\gamma_{22}\rho_{22} + \mathcal{I}\rho_{20} - \mathcal{I}\rho_{02} - \mathcal{I}\rho_{21} + \mathcal{I}\rho_{12}
\]

\[
\dot{\rho}_{01} = (\gamma_{10} + \mathcal{I}\delta_1)\rho_{01} - \mathcal{I}\rho_{10} - \mathcal{I}\rho_{21} + \mathcal{I}\rho_{12}
\]

\[
\dot{\rho}_{02} = (\gamma_{10} - \mathcal{I}\delta_2)\rho_{02} - \mathcal{I}\rho_{00} + \mathcal{I}\rho_{12} - \mathcal{I}\rho_{01}
\]

\[
\dot{\rho}_{12} = (\gamma_{21} + \mathcal{I}\delta_2 - \mathcal{I}\delta_1)\rho_{12} - \mathcal{I}\rho_{10} + \mathcal{I}\rho_{21} - \mathcal{I}\rho_{12}
\]

(1)

where \(\rho_{nm}\) represents the slowly-varying part of the density matrix element \(\rho_{mn}\). If \(m = n\), \(\rho_{nm} = \rho_{nm}\); otherwise, \(\rho_{02} = \rho_{02} \exp(-\mathcal{I}\omega_{20}t), \rho_{12} = \rho_{12} \exp(-\mathcal{I}\omega_{12}t), \) and \(\rho_{01} = \rho_{01} \exp(-\mathcal{I}\omega_{01}t)\). The definitions of other parameters are given in Table I.

In (1), we have assumed the pump beam intensity is much stronger than that of the signal beam such that the signal beam can be treated as a perturbation. It is worthwhile to mention that in our numerical calculations below, we did not make such an approximation but results we obtained were very close to the analytical results from (1) in the case that the signal intensity is much lower than that of the pump intensity. When the detunings of both pump and signal beams are small, the steady state solution of the slowly varying density matrix element \(\sigma_{21}\) is given by (2), shown at the bottom of the page, where \(W = 2\mathcal{E}\gamma_{20}/(\gamma_{20}^2 + \delta_2^2)\) is the pumping rate.

From (2), the dielectric constant \(\varepsilon(\omega_0)\) as seen by the signal beam can be obtained as follows:

\[
\varepsilon(\delta_1) = \varepsilon_{\text{vac}} + \frac{2}{\varepsilon_0 \Gamma_{10} / V} \varepsilon(\sigma_{11} - \sigma_{22}) \sigma_{21} \varepsilon(\delta_1) \equiv \varepsilon(\delta_1) + \varepsilon''(\delta_1)
\]

where \(\varepsilon_{\text{vac}}\) is the background dielectric constant, \(\varepsilon_0\) is the dielectric constant in the vacuum, \(\Gamma\) is the optical confinement factor, and \(V\) is the volume of the active region, i.e., the QW. At steady state, \(\sigma_{11} = \sigma_{22} \approx -1\). From (3), we can further derive the real part of the refractive index, \(\varepsilon'(\delta_1)\) and the slow-down factor \(S\) as functions of the pump-signal detuning \(\delta_1\) using the following relationship:

\[
n(\delta_1) = \sqrt{\frac{\varepsilon'(\delta_1)^2 + \varepsilon''(\delta_1)^2}{2}}^1/2 + \varepsilon(\delta_1)
\]

\[
\alpha(\delta_1) = \sqrt{\frac{\varepsilon'(\delta_1)^2 + \varepsilon''(\delta_1)^2}{2}} - \varepsilon(\delta_1) - \text{sign}(\varepsilon''(\delta_1))
\]

\[
S(\delta_1) = \left[n(\delta_1) + \omega_p \frac{\partial n(\delta_1)}{\partial \delta_1}\right]_{\delta_1=0}.
\]

(4)

It is worthwhile to note that although, it is not explicitly mentioned, the pump detuning needs to be smaller than the homogeneously broadened linewidth of level [2] such that the effective

![Image](image_url)

Table I: Definitions of the Symbols and Their Units Used in This Paper

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
<th>Unit</th>
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<tbody>
<tr>
<td>(\rho_{nm})</td>
<td>density matrix element</td>
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</tr>
<tr>
<td>(\sigma_{nm})</td>
<td>slowly-varying density matrix element</td>
<td></td>
</tr>
<tr>
<td>(\gamma_{nm})</td>
<td>dephasing rate between (</td>
<td>\psi_{nm}\rangle) and (</td>
</tr>
<tr>
<td>(\Gamma_{nm})</td>
<td>carrier relaxation rate between (</td>
<td>\psi_{nm}\rangle) and (</td>
</tr>
<tr>
<td>(\hbar\omega_{nm})</td>
<td>energy separation between (</td>
<td>\psi_{nm}\rangle) and (</td>
</tr>
<tr>
<td>(\mu_{nm})</td>
<td>dipole moment between (</td>
<td>\psi_{nm}\rangle) and (</td>
</tr>
<tr>
<td>(\omega_p)</td>
<td>pump frequency</td>
<td>Hz</td>
</tr>
<tr>
<td>(\omega_c)</td>
<td>signal frequency</td>
<td>Hz</td>
</tr>
<tr>
<td>(\hbar)</td>
<td>single photon detuning ((\delta_0 = \omega_p - \omega_{20}))</td>
<td>eV</td>
</tr>
<tr>
<td>(\delta_0)</td>
<td>two photon detuning ((\delta_0 = \omega_p - \omega_{21} - \delta_0))</td>
<td>eV</td>
</tr>
<tr>
<td>(\Omega_p)</td>
<td>pump Rabi frequency ((\Omega_p = \mu_0 E_p / 2\hbar))</td>
<td>Hz</td>
</tr>
<tr>
<td>(\omega_s)</td>
<td>signal Rabi frequency ((\omega_s = \mu_0 E_s / 2\hbar))</td>
<td>Hz</td>
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pumping of carriers from $|0\rangle$ to $|2\rangle$ can be achieved. The dependence on the pump detuning will be discussed in Section II-B.

We have performed numerical calculations using parameters given in Table II. Fig. 2 shows the calculated real part of the refractive index, the absorption coefficient and the slow-down factor versus the pump-signal detuning which is normalized to the excitonic dephasing rate. The negative absorption represents the signal gain. (b) The calculated slow-down factor near zero pump-signal detuning. The parameters used in these calculations are given in Table II.

Fig. 2. (a) Calculated absorption (solid line) and refractive index (dashed line) spectra experienced by the signal beam in an RTLS configuration near zero pump-signal detuning, which is normalized to the excitonic dephasing rate between two upper levels. The negative absorption represents the signal gain. (b) The calculated slow-down factor near zero pump-signal detuning. The parameters used in these calculations are given in Table II.

B. Parametric Analysis of RTLS

In this sub-section, we will systematically study the slow-down factor and the operating bandwidth as functions of various system and material parameters including pump intensity, excitonic dephasing rates ($\gamma_{30}$ and $\gamma_{21}$), and the pump detuning ($\delta_p$). Numerical calculations will be performed to obtain both the slow-down factor and the operating bandwidth dependences on each individual parameter with other parameters fixed at values given in Table II. The results are shown in Fig. 3(a)–(d). The discussions of the dependence on each parameter are summarized in the following.

1) Dependence on the Pump Intensity [Fig. 3(a)]: As shown in Fig. 3(a), the maximum slow-down factor does not increase monotonically with respect to the pump intensity. It increases initially with the pump intensity and then saturates before rolling off at high pump intensity. On the other hand, the bandwidth increases monotonically with the pump intensity. This can be explained as follows. The depth of the gain peak saturates at a certain pump intensity due to the population depletion, while the width of the gain peak increases monotonically with the pump intensity. The slow-down factor is proportional to the depth of the gain peak and is inversely proportional to the width of the gain peak [4]. However, the bandwidth is only proportional to the width of the gain peak. The dependence in Fig. 3(a) is similar to what has been observed in slow light using EIT and CPO [4]. The dependence on the pump intensity also provides one possible tuning mechanism for the slow-down factor.

2) Dependence on the Exciton Dephasing Rate [Fig. 3(b)]: As shown in Fig. 3(b), the slow-down factor exhibits a strong dependence on the interband exciton dephasing rate $\gamma_{21}$ in semiconductor heterostructures such as QWs. For materials and structures such as quantum dots (QDs) that possess a weaker exciton dephasing, the slow-down factor can be considerably increased. For example, it has been reported that the uniform InAs QDs possess an exciton dephasing rate of 5 THz at room temperature [25], which is about a factor of 2 slower than that in a QW. This corresponds to a slow-down factor of $\sim$470. The bandwidth relationship in Fig. 3(b) shows that the bandwidth of this system is determined by the exciton dephasing rate and the bandwidth decreases as the slow-down factor increases. This agrees with the general bandwidth-delay product tradeoff [4], [11].

3) Dependence on $\gamma_{30}$ [Fig. 3(c)]: Neither the slow-down factor nor the bandwidth depend strongly on the intersubband dephasing rate as long as the population inversion can be established between the two lower energy levels.

4) Dependence on the Pump Detuning $\delta_p$ [Fig. 3(d)]: The major difference between SRS and the proposed RTLS is the pump detuning. When the pump frequency is detuned off the resonance, that is when the pump detuning is larger than the homogeneously broadened linewidth of level $|2\rangle$, the resonance

### Table II

<table>
<thead>
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<th>Parameters</th>
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<tbody>
<tr>
<td>$1/\tau_{10}$</td>
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<tr>
<td>$1/\tau_{21}$</td>
</tr>
<tr>
<td>$\hbar \gamma_{10}$</td>
</tr>
<tr>
<td>$\hbar \gamma_{21}$</td>
</tr>
<tr>
<td>$\mu_{23}/e = \mu_{21}/e$</td>
</tr>
<tr>
<td>$V/\Gamma_{conf}$</td>
</tr>
<tr>
<td>Pump intensity</td>
</tr>
<tr>
<td>Signal wavelength</td>
</tr>
<tr>
<td>Pump detuning $\delta_p$</td>
</tr>
<tr>
<td>200 fs</td>
</tr>
<tr>
<td>1 ns</td>
</tr>
<tr>
<td>10 meV</td>
</tr>
<tr>
<td>5 meV</td>
</tr>
<tr>
<td>19 Å</td>
</tr>
<tr>
<td>5x10^{-3} nm^3</td>
</tr>
<tr>
<td>8 kW/cm^2</td>
</tr>
<tr>
<td>1.55 μm</td>
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condition starts to fall off, and as a result the slow-down factor decreases substantially. Using the following relationship that the radiative lifetime of level $|2\rangle$ is given by $\tau_2 \sim 1/(\gamma_{12} + \gamma_2)$, the homogeneously broadened linewidth in our calculations was around $\Delta\omega_{\text{p}}$, i.e., 10 meV. As shown in Fig. 3(d), a substantial reduction of the slow-down factor is observed when the pump detuning is greater than 10 meV. This result again verifies the importance of the resonance between the pump beam and the three-level system.

III. RTLS IN GENERAL THREE-LEVEL SYSTEMS AND SUPERLUMINAL LIGHT

In a general three-level system, the ratio $\eta = \Gamma_{21}/\Gamma_{10}$ is not necessarily much smaller than unity as assumed in the previous Section. In this Section, we will discuss the response of the signal beam in the presence of the strong pump in a general RTLS configuration with different system parameters. We will show that in addition to the slow light, superluminal light is also possible. To better summarize the results, we first define two quantities as follows:

$$
\zeta_1 \equiv [1 - \eta + \Gamma_{22}/2(\gamma_{21} + \gamma_{10})],
$$

$$
\zeta_2 \equiv [\gamma_{10}(1 + \eta) + \Gamma_{22}/2(\gamma_{21} + \gamma_{10})].
$$

In (5), $\Gamma_{22} = \Gamma_{21} + \Gamma_{10}$. We found that conditions $\zeta_1 < \zeta_2$ and $\zeta_1 > \zeta_2$ correspond to the slow light and the superluminal light at zero pump-signal detuning, respectively.

The above two conditions can be further divided into three different cases based on the relative position of $\eta$ with respect to $1-\Gamma_{22}/2\gamma_{21}$ and $1+\Gamma_{22}/2\gamma_{21}$. The imaginary part of the susceptibility $\chi$ and the slow-down factor for the above six different cases are shown in Fig. 4. In most of the materials, the dephasing rates are much larger than the carrier relaxation rates and therefore it is unlikely that $\eta$ will fall between $1-\Gamma_{22}/2\gamma_{21}$ and $1+\Gamma_{22}/2\gamma_{21}$ as both quantities approach unities. Therefore, we will focus only on the difference between $\eta < 1$ and $\eta > 1$.

If $\eta < 1$, the population inversion and hence the gain can be established between $|2\rangle$ and $|1\rangle$. On the other hand, if $\eta > 1$, the signal will experience absorption due to the presence of carriers in level $|1\rangle$ at a steady state. In the case of $\eta < 1$, $\zeta_1$
and \( \zeta_2 \) are always positive. When the pump intensity and the corresponding \( \zeta_2 \) is small, we obtain \( \zeta_1 < \zeta_2 \) and the slow light as shown in Fig. 4(d). This case was discussed extensively in the previous section. If the pump intensity continues to increase until the following condition is met:

\[
\Omega_p^2 > \frac{\gamma_0^3}{\gamma_1 + 2\gamma_0}
\]

then the relationship between \( \zeta_1 \) and \( \zeta_2 \) becomes \( \zeta_1 > \zeta_2 \) and the signal experiences the superluminal propagation. In (6), we have assumed the dephasing is much faster than the carrier relaxation. As shown in Fig. 4(a), the strong pump splits the single gain peak in Fig. 4(d) and “burns” a hole around the zero pump-signal detuning. A similar but opposite behavior is observed for the case of \( \eta > 1 \) in which the signal experiences net loss at zero pump-signal detuning. At small pump intensity, we have a single absorption peak and therefore superluminal light as shown in Fig. 4(f). When the pump intensity is increased such that (6) is satisfied again, the single absorption peak is split into two resonances. The slow light occurs at the center (zero pump-signal detuning) of the two resonances as shown in Fig. 4(c). Note that Fig. 4(f) is identical to a (zero pump-signal detuning) of the two resonances as shown in Fig. 4(c). This is because when \( \eta > 1 \), we can no longer assign either level \( |0\rangle \) or level \( |1\rangle \) as the ground state. As pump intensity increases to overtake the decoherence between \( |1\rangle \) and \( |0\rangle \), this situation becomes EIT-like.

IV. LIMITATIONS OF SLOW LIGHT VIA RTLS

While the slow-down factor plays a critical role in nonlinear slow light devices, it is also important to find out the upper limit of the length of the functional device area or, equivalently, the total delay. In the case of EIT and CPO based slow light optical buffers, the maximum delays are limited by finite absorption [27], [28]. On the other hand, in optical-amplification-based slow light devices including the RTLS system discussed above, the total delays are limited by pump depletion due to high signal gain and amplified spontaneous emission (ASE) noise due to gain saturation [3], [29], [30]. When the signal intensity becomes large enough that the gain saturation becomes important, the ASE noise will degrade the signal-to-noise ratio (SNR). In addition, it is essential to keep the pump intensity constant throughout the entire device area. The possible pump depletion issue may be alleviated by distributing the pump beam over the device length.

The limit of the total delay in an RTLS system is governed by the delay-bandwidth product which is on the order of unity [4]. The total delay is limited to a few pulse widths. This places the upper limit on the number (in the unit of bits) of simultaneous nonlinear digital signal operations that can be performed at the same time. If a larger processing capacity is desired, it is possible to cascade a series of RTLS slow light elements and unidirectional optical attenuators in an alternating fashion to reduce the signal intensity [31], and therefore avoid the gain saturation.

To further reduce the adverse effect from the ASE, we also propose to fabricate a two-dimensional photonic bandgap structure surrounding the signal waveguide. Because the signal beam is highly directional along the direction of the waveguide, the properly alignment of the photonic bandgap with the signal spectrum can suppress the spontaneous emission along directions other than the waveguide orientation. The ASE noise can therefore be reduced.

V. CONCLUSION

In summary, we have proposed a novel slow light mechanism that is suitable for high bandwidth all-optical signal processing by enhancing the nonlinear optical response through the compression of the signal energy density. The mechanism is based on a resonant three level \( \Lambda \) system (RTLS) in which a strong pump beam is coupled to the ground state and the upper-most state of a three-level system. By properly choosing the three-level configuration in a semiconductor heterostructure, population inversion can be established between the upper-most state and the intermediate state to provide a large gain for the signal beam and therefore induce a slow signal group velocity. Our numerical calculations show that in a typical semiconductor quantum heterostructure such as quantum well or an array of quantum dots, the three energy levels can be chosen to be the light hole, the heavy hole and the first conduction subband, respectively. The calculated slow-down factor and the slow-down-bandwidth product are 145 and >200 THz, respectively. This bandwidth is enough to process a digital signal with a bit rate > 100 Gbit/s without generating much distortion. We have also analyzed a general scheme of an RTLS system and have shown that both slow light and superluminal light are possible with the control of external pump intensity. Finally, we discussed the limitation of the maximum nonlinear slow light device length and provided potential solutions to address two major issues: pump depletion and ASE noise.

REFERENCES


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