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<th><strong>Title</strong></th>
<th>Tunable flat-band slow light via contra-propagating cavity modes in twin coupled microresonators</th>
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<td><strong>Author(s)</strong></td>
<td>Ang, Thomas Y. L.; Ngo, Nam Quoc</td>
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1. INTRODUCTION

Slow light (SL) holds the key to increase the speed of optical communications [1] as it offers the abilities in delaying, coherently stopping, and storing data trains [2], which are needed for enhanced performances in optical networks. The most simple and compact scheme to generate SL in traveling-wave microresonators (MRs) can be achieved in one of two ways. The first way is by resonance enhancement via one single MR—the group delay $t_g$ is increased by forcing the light to circulate many times in the MR. In this case, the MR can be either coupled to one bus waveguide (WG) [3,4], which we will term as the 1-cavity-1-bus configuration, or to two bus WGs [5,6], which we will term as the 1-cavity-2-buses configuration. The second way is by optically mimicking the atomic concept of electromagnetically induced transparency (EIT) [7]—this is known as coupled-resonator-induced transparency (CRIT) and is typically realized by coupling two MRs together [8–11] such that the coupled MRs behave like atoms with EIT settings.

A practical SL system should ideally have (1) a large $t_g$ enhancement and (2) flat or minimal dispersion in the $t_g$ and transmission $T$ spectra (with transmission $T=1$) over a large usable resonance bandwidth $\Delta f_w$. To quantify criteria (1) and (2), we use the delay-bandwidth product (DBP), which is defined as $\text{DBP} = f_{\text{max}} \times \Delta f_w = \text{constant}$ [12], where $f_{\text{max}}$ is the maximum group delay at resonance. The DBPs of the above-mentioned resonance enhancement scheme are computed to be $\sim 2/\pi$ and $\sim 1/(2\pi)$ for the 1-cavity-1-bus and 1-cavity-2-buses configurations, respectively, while that of the above-mentioned CRIT scheme with a two coupled MRs is $\sim 1/\pi$. These DBPs are computed using the full width at half maximum (FWHM) as the usable resonance bandwidth $\Delta f_w$. In reality, to minimize higher-order dispersion, $\Delta f_w \ll \text{FWHM}$. This implies lower DBPs than the above computed figures. A lower DBP generally means that a large group delay $t_g$ results in a much smaller usable resonance bandwidth $\Delta f_w$. This will restrict the use of these SL media in transmission systems with ultrashort pulses. Though cascading multiple MRs (or unit cells) [12–18] will increase $t_g$, the DBP remains approximately the same as that of a single MR in the resonance enhancement scheme [3–6] or the twin coupled MRs in the CRIT scheme [8–11] due to the formation of ripples in the resonance spectra that will distort the signal and consequently reduce $\Delta f_w$.

In this work, we look into the use of a twin coupled MRs scheme (cf. Fig. 1) to realize an SL system that has sufficiently large group delay $t_g$ and high transmission $T$, with minimal dispersion in $t_g$ and $T$ over a wide bandwidth (i.e., flat-band SL with enhanced DBPs). As shown in Table 1, the proposed scheme improves the DBP by 3- to 24-fold as compared to conventional MR-based SL systems. Fabrication tolerance and cavity losses analyses have also revealed that the proposed scheme is rather robust to the fabrication errors and limitations of current state-of-the-art semiconductor processing technology. © 2012 Optical Society of America

modes. Note that all the components are single-moded in this work. In Fig. 1, the electric fields in each MR are represented by \( a_n^+, b_n^+, c_n^+, \) and \( d_n^+ \), where \( x = -(x = +) \) denotes the CW (CCW) mode, while \( n = 1 \) (\( n = 2 \)) denotes the left (right) MR. Likewise, the electric fields in the port WG are represented by \( A_n^+, B_n^+, C_n^+, \) and \( D_n^+ \), with \( x = -(x = +) \) denoting the backward (forward) propagating mode, while \( n = 1 \) (\( n = 2 \)) denotes the side of the WG located below the left (right) MR. The evanescent coupling between the MRs at coupling junction (CJ) 1 can be described as

\[
[c_2^- d_2^- d_2^+ c_2^+]^T = S_1 [c_1^+ d_1^+ d_1^- c_1^-]^T, \tag{1}
\]

while the evanescent coupling between the MR and WG at CJs 2 and 3 can be written as

\[
\begin{align*}
[ a_1^- & b_1^- a_1^+ b_1^+]^T = S_2 [A_1^+ B_1^- B_1^+ A_1^-]^T, \tag{2} \\
[ a_2^- & b_2^- b_2^+ a_2^+]^T = S_3 [a_2^+ b_2^- b_2^+ a_2^-]^T. \tag{3}
\end{align*}
\]

in which \( S_i \) (\( i = 1, 2, \) or 3) is termed as the coupling matrix that is defined as

\[
S_i = \begin{bmatrix} [U_i] & 0 \\ 0 & [U_i] \end{bmatrix}, \quad \text{with} \quad U_i = \begin{pmatrix} r_i/(\beta_j) & -1/(\beta_j) \\ (\kappa_j + r_j)/(\beta_j) & r_i/(\beta_j) \end{pmatrix}, \tag{4}
\]

where \( j = \sqrt{-1} \), while \( r_i \) and \( \kappa_j \) are, respectively, the through and cross coupling coefficients. Do note that \( k_j^2 + r_j^2 = 1 - \sigma_j^2 \) represents the attenuation constant of the coupler at each CJ, in which \( \sigma_j \) quantifies for the coupler loss (\( \sigma_j = 0 \) for a lossless coupler). The subscript \( i = 1, 2, \) or 3 represents the position of the CJs in Fig. 1, where \( i = 1, 2, \) and 3 corresponds to CJ 1, CJ 2, and CJ 3, respectively. Within the MRs, the electric fields are described as

\[
\begin{align*}
[c_1^+ d_1^+ d_1^- c_1^-]^T &= P_{a_1} [a_1^+ b_1^- b_1^+] \tag{5} \\
[a_2^+ b_2^- b_2^+ a_2^-]^T &= P_{a_2} [c_2^+ d_2^- d_2^+ c_2^-] \tag{6}
\end{align*}
\]

in which \( P_{a_n} \) (\( n = 1 \) or 2) is termed as the propagation matrix that is defined as

\[
P_n = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & \tau_n^{3/4} & \tau_n^{-1/4} & 1 \\ \tau_n^{-1/4} & 0 & 0 & 0 \end{pmatrix} \tag{7}
\]

where \( \tau_n \) is the round-trip amplitude transmission coefficient (lossless MR: \( \tau_n = 1 \)) and \( \delta_n = 2\pi R_n/\beta_n \) is the round-trip phase shift, in which \( R_n \) and \( \beta_n \) are, respectively, the bend radius and propagating constant of the MR, with \( n = 1 \) (\( n = 2 \)) denoting the left (right) MR. The electric fields in the bus WG can be described as

\[
[A_2^+ A_2^-]^T = \begin{pmatrix} \exp(j\beta_w L_w) & 0 \\ 0 & \exp(-j\beta_w L_w) \end{pmatrix} [A_1^+ A_1^-]^T, \tag{8}
\]

where \( \beta_w \) and \( L_w \) are, respectively, the propagating constant of the bus WG and the separation distance between the MRs. Setting \( B^2 = 0 \) (i.e., only one input) and using Eqs. (1)-(8), the fields propagating in the bus WG can then be described as

\[
\begin{align*}
[A_1^+ \exp(-j\beta_w L_w) & B_2^+ 0 A_1^- \exp(j\beta_w L_w)]^T \\
= Y & [A_1^+ B_1^- B_1^+ A_1^-]^T. \tag{9}
\end{align*}
\]

where \( Y = S_1 S_2 S_3 S_4 \) is a \( 4 \times 4 \) matrix. We are interested to solve for \( \xi_T \) and \( \xi_R \), and \( \xi_T = B^+ / B^+1 \) and \( \xi_R = B^- / B^-1 \), which are, respectively, the complex electric field transmissivities at the through and reflection ports. To do so, we recast Eq. (9) as

\[
\begin{align*}
A_1^+/B_1^+ &= \begin{bmatrix} Y_{11} & Y_{12} & Y_{13} & Y_{14} \\ Y_{21} & Y_{22} & Y_{23} & Y_{24} \\ Y_{31} & Y_{32} & Y_{33} & Y_{34} \\ Y_{41} & Y_{42} & Y_{43} & Y_{44} \end{bmatrix}^{-1} \\
&\times \begin{bmatrix} -Y_{13} \\ -Y_{23} \\ -Y_{33} \\ -Y_{43} \end{bmatrix}. \tag{10}
\end{align*}
\]

In this work, \( \xi_T \) and \( \xi_R \) are collectively termed as \( \xi_q \) (\( q = T \) or \( R \)), where the subscript \( T(R) \) denotes the through (reflection) port. Note that \( \xi_q \) contains all the information needed to characterize the SL properties: \( |\xi_q|^2 \) gives the transmission \( T_q \), while \( \Phi_q = \arg(\xi_q) \) is the MR-induced effective phase shift of the output light that determines the group delay \( t_g \), which can be defined as \( t_{g,q} = t_{c,q} \Phi_q / \delta_s \), where \( t_{c,q} \) is the cavity round-trip time.

### 3. Generating Flat-Band Slow Light

#### A. General Operating Mechanism

To understand the operating mechanism behind the proposed scheme, it is instructive to first analyze a single MR system (i.e., only MR 1 exists in Fig. 1)\[3,4]\) and a twin coupled MRs system that has only one cavity directly coupled to the bus WG (i.e., \( k_3 = 0 \) in Fig. 1)\[8,10,11]\). We will assume that the losses of the MRs and couplers are negligible (i.e., \( \tau_n = 1 \) and \( \sigma_j = 0 \)) in this section. For simplicity, only the case of coresonant cavities (i.e., \( \delta_1 = \delta_2 = \delta \)) is considered in this work. This will generate flat-band SL centered at the normalized resonance frequency \( \delta = 2\pi m \) (where \( m = 1, 2, 3, \ldots \)) if certain physical conditions (governed by Eq. (10), as derived later) are met.

For the single MR system, the complex transmissivity \( \xi_T \) has the expression \( \xi_T = (\exp(j\delta) - r_q)/(r_q \exp(j\delta) - 1) \). Consequently, there is only one eigenmode that is resonant at \( \delta = 2\pi m \). A sharp Lorentzian resonance lineshape is then

\[
T(x) = 1 - \frac{1}{1 + (x - \delta)^2 / \gamma^2}, \quad \gamma = 2\pi / (k_1 - k_2)
\]
formed at $\delta = 2\pi m$, as shown in the transmission and group delay spectra in Figs. 2(ai) and 2(aiii) in blue line plots, with a rapid phase shift of $2\pi$ across the resonance in Fig. 2(aii). The eigenmode (at $\delta = 2\pi m$) of the single MR system is denoted as $\delta_0$. When a second MR is coupled to the single MR such that it is not directly coupled to the bus WG (i.e., $\kappa_3 = 0$ in Fig. 1), $\xi_T$ becomes $\xi_T = (\xi_2 \exp(j\delta) - r_2)/(\xi_2 \exp(j\delta) - 1)$, where $\xi_2 = (\exp(j\delta) - r_1)/(r_1 \exp(j\delta) - 1)$ is the loading factor due to the addition of the second MR. This results in two eigenmodes $\delta_1$ and $\delta_2$ that can be approximated as

$$\delta_1 = \delta_0 - \sin^{-1} \kappa_1, \quad \delta_2 = \delta_0 + \sin^{-1} \kappa_1,$$

(11)

where $\delta_0 = 2\pi m$ is the eigenmode of the above-mentioned single MR system. Thus, the resonance frequency $\delta_0$ of the single MR is split into $\delta_1$ and $\delta_2$ with the mode splitting being controlled by $\kappa_1$. As a result, the resonance spectra have the shape of a two-split Lorentzian, as shown in Figs. 2(ai) and 2(aiii) in red line plots, with the effective phase shift being split into two $2\pi$ swings in Fig. 2(aii). Finally, if both MRs are coupled to the bus WG (i.e., $\kappa_3 \neq 0$) such that one has the proposed configuration in this work (cf. Fig. 1), contra-propagating cavity modes are excited. Then, both forward and backward transmissions, i.e., $T_T = |\xi_T|^2$ and $T_R = |\xi_R|^2$, are observed. Note that $r = r_2 = r_3$ and $\kappa = \kappa_2 = \kappa_3$. Using this and Eq. (10), the complex transmissivities $\xi_T$ and $\xi_R$ can be expressed as

![Fig. 1. (Color online) Schematic of the proposed twin coupled traveling-wave MRs.](image)

![Fig. 2. (Color online) The transmission, effective phase shift, and group delay spectra of different resonator systems. In (ai) to (aii), the plots in blue show the spectra at the through port of a single resonator system (i.e., only resonator 1 exists in Fig. 1) with $\kappa_2 = 0.08, T_1 = 1$. The plots in red in (ai) to (aiii) show the spectra at the through port of a twin coupled resonators system that has only one resonator directly coupled to the bus WG (i.e., $\kappa_3 = 0$ in Fig. 1) with $\kappa_1 = 0.05, \kappa_2 = 0.08, r_1 = r_2 = 1$. The spectra at the through port of our proposed twin coupled resonators with $\kappa_1 = 0.05, \kappa_2 = \kappa_3 = 0.08, \kappa_1 = 0.05, \kappa_2 = \kappa_3 = 0.08$, and $r_1 = r_2 = 1$ are shown in (bi) to (biii), while those at the reflection port are shown in (ci) to (ciii).](image)
\[ \xi_T = -\frac{2r^2 \cos(2\delta) + 4rr_1(r^2 + 1) \cos(\delta) - 2r^2_1(r^4 + 1) + r^2(r^2 - 4) + 1}{\exp(-j\delta)[4rr_1 \exp(\delta) + \exp(-j\delta)] - [r^4 \exp(2j\delta) + \exp(-2j\delta)] - 2r^2[1 + 2r^2_1]} \cdot \]
\[ \xi_R = \frac{2j[\cos(\delta) - 2 \cos^2(\delta)]r^2 + [2r^2 - r^4 - 1]r^2_1 - r^4 + 1}{\exp(-j\delta)[r^2 \exp(j\delta) + \exp(-j\delta) - 2rr_1][1 - r^2_1]^{1/2}[1 - r^2]} . \] (12)

For \( \xi_q \) (\( q = T \) or \( R \)) in Eq. (12), four eigenmodes, which we will denote as \( \delta_{1,1}, \delta_{1,2}, \delta_{2,1}, \) and \( \delta_{2,2} \), are formed. Consequently, as illustrated in Figs. 2(bi) and 2(ci), there are now two (four) sharp peaks and four (two) sharp dips in the transmission spectra of the through (reflection) port due to the newly formed split modes \( \delta_{1,1}, \delta_{1,2}, \delta_{2,1}, \) and \( \delta_{2,2} \). These are in contrast to the earlier mentioned cases of \( \kappa_3 = 0 \) (i.e., dotted curves of Fig. 2), in which there are only two split modes \( \delta_1 \) and \( \delta_2 \). The new split modes \( \delta_{1,1}, \delta_{1,2}, \delta_{2,1}, \) and \( \delta_{2,2} \) in Figs. 2(bi) and 2(ci) can be described as

\[ \delta_{1,1} = \delta_1 - \kappa^2/2 = \delta_0 - \sin^{-1} \kappa_1 - \kappa^2/2, \]
\[ \delta_{1,2}/\delta_1 + \kappa^2/2 = \delta_0 - \sin^{-1} \kappa_1 + \kappa^2/2, \]
\[ \delta_{2,1} = \delta_2 - \kappa^2/2 = \delta_0 + \sin^{-1} \kappa_1 - \kappa^2/2, \]
\[ \delta_{2,2} = \delta_2 + \kappa^2/2 = \delta_0 + \sin^{-1} \kappa_1 + \kappa^2/2. \] (13)

It is evident from Eq. (13) that \( \kappa \) controls the formation of the multipeaks (dips) that appear in the transmission \( T_q \) spectra of the reflection (through) ports. For practical SL applications, the multipeaks and dips must be flattened. It is generally not possible to simultaneously flatten both the transmission \( T_q \) and group delay \( \tau_q \) spectra of any MR system due to its Hilbert transform properties [12]. Nonetheless, the group delay dispersion (GDD) of our device is found to be minimal when the \( T_q \) spectrum is maximally flat. Thus, in this work, we define flat-band SL as one with (1) flat-band \( T_q \)'s \( T_q = 1 \), and (3) minimal GDD (i.e., close to flat-band \( T_q \)). To achieve such flat-band SL at both ports of our device, one only needs to control the mode splitting via Eq. (13) such that the multipeaks of the various split modes become indistinguishable and merge into one single broadened peak that is maximally flat at \( \delta = 2\pi m \) in the resonance spectra, while at the same time producing \( T_q = 1 \). This is intuitively shown in Fig. 3: the multipeaks move inwards (in the direction of the arrows) and merge into one single, flattened peak as \( \kappa_3 \) is progressively decreased. The initial effective phase shift of the two (four) \( \pi \) swings converges into one single \( 2\pi (4\pi) \) for the through (reflection) port when flat-band SL is achieved. In the next section, we look into the conditions needed to achieve flat-band SL.

B. Optimization for Flat-Band SL

From Fig. 2(a), one can observe that, at the through port, there are two peaks (i.e., \( \delta_1 \) and \( \delta_2 \)), while at the reflection port, there are four peaks (i.e., \( \delta_{1,1}, \delta_{1,2}, \delta_{2,1}, \) and \( \delta_{2,2} \)). Flat-band SL for the proposed twin coupled MRs can be generated at the through port if the two peaks of \( \delta_1 \) and \( \delta_2 \) are converted into a single flattened peak at \( \delta = 2\pi m \). This means

\[ \delta_1 = \delta_2 = \delta_0 = 2\pi m, \quad \delta_{1,1} = \delta_{2,1} = 2\pi m - \kappa^2/2, \]
\[ \delta_{1,2} = \delta_{2,2} = 2\pi m + \kappa^2/2. \] (14)

Fig. 3. (Color online) Evolution in the resonance spectra towards flat-band SL for the proposed device with \( \kappa_3 = \kappa_1 = \kappa = 0.3 \) as \( \kappa_3 \) is decreased progressively. Note that the horizontal arrows point in the direction of decreasing \( \kappa \). Resonance spectra at the through port are shown in (ai) to (aiii), while those at the reflection port are shown in (bi) to (biii).
Likewise, at the reflection port, flat-band SL occurs when the four peaks of \( \delta_{1,1}, \delta_{1,2}, \delta_{2,1}, \) and \( \delta_{2,2} \) are converted into a single flattened peak at \( \delta = 2\pi m \). This means
\[
\delta_1 = \delta_2 = \delta_{1,1} = \delta_{1,2} = \delta_{2,1} = \delta_{2,2} = 2\pi m. \tag{15}
\]
Solving Eqs. (14) and (15) together with the condition that \( \partial^2_{b}(\xi_{b}(\delta_0))/\partial\delta^2 = 0 \) gives
\[
\kappa_{s,T} = \kappa_1 = \frac{\kappa^2}{2 - \kappa^2}, \quad \kappa_{s,R} = \kappa_1 = \frac{2^{1/2}\kappa^2}{2 - \kappa^2 + \sqrt{2(1 - \kappa^2)}}. \tag{16}
\]
where \( \kappa_{s,T} \) and \( \kappa_{s,R} \) are the values of \( \kappa_1 \) needed to achieve flat-band SL at the through port and the reflection port, respectively. Using Eq. (16), we have plotted the different \( (\kappa_1, \kappa) \) needed to achieve flat-band SL in Fig. 4. It can be seen that, for both ports, \( \kappa > \kappa_1 \) is required for flat-band SL. The value of \( \kappa_1 \) needed for flat-band SL at the through port is larger than that of the reflection port, given the same \( \kappa \). This means \( \kappa_{s,T} > \kappa_{s,R} \), with \( \kappa_{s,T} = \Psi \), where \( \Psi = 2^{1/2} + 2r/(1 + r^2) \). In general, \( \kappa_{s,T} = 2.4\kappa_{s,R} \) for \( \kappa < \sim 0.7 \) (cf. Fig. 4).

Using different \( (\kappa_1, \kappa) \) from Fig. 4, the resonance spectrums are then plotted in Fig. 5 for both ports. It is evident that maximally flat transmission \( T_q \) spectrums, which are centered at \( \delta = 2\pi m \), can be achieved with \( T_q = 1 \) and minimal GDD by controlling \( \kappa_1 \) in relation to \( \kappa \). The bandwidth of the flat-band SL increases with \( \kappa \), albeit smaller group delay as \( DBP = constant \). This characteristic of the \( DBP = constant \) can also be verified in the effective phase shift responses in Figs. 5(aii) and 5(bii): for all \( (\kappa_1, \kappa) \), there is a fixed phase swing of \( \sim 2\pi \) (\( \sim 4\pi \)) for the through (reflection) port. We can then deduce that the DBP of our proposed device for the through (reflection) port is \( 2/\pi \) (\( 4/\pi \)). Thus, the DBPs of our proposed device will outperform other MR-based SL systems (cf. Table 1).

4. CHARACTERIZING THE FLAT-BAND SLOW LIGHT

We now characterize the flat-band SL in terms of the maximum group delay at resonance \( \gamma_{y,\kappa} \) and the usable resonance bandwidth \( \Delta f_{u, \kappa} \) where the subscript \( T(R) \) denotes the through (reflection) port. We define \( \gamma_{y,\kappa} \) and \( \Delta f_{u, \kappa} \) as \( \gamma_{y,\kappa} = \gamma_{y,\kappa} \times t_{rt} \) and \( \Delta f_{u, \kappa} = FSR \times \Delta \delta_{u, \kappa}/(2\pi) \), respectively, where \( t_{rt} \) is the normalized group delay, \( t_{rt} = 1/FSR \) the cavity round-trip time, \( FSR = c/(n_g L_c) \) is the free spectral range (in Hz), \( n_g \) is the group effective index, \( L_c \) is the length of the cavity, and \( \Delta \delta_{u, \kappa} \) is the normalized usable bandwidth of the flat-band SL that has maximally flat transmission \( T_q \) and minimal GDD. Using Eqs. (11)–(16), \( \gamma_{y,\kappa} \) for the two output ports can be expressed as
\[
\gamma_{y,T,R} = \frac{3 + r^2}{1 - r^2} t_{rt}, \quad \Delta f_{u,T,R} = \frac{r B^{1/2} + r^2 - 3}{r B^{1/2} - r^2 - 1/2} t_{rt}, \tag{17}
\]
where \( B = 4 - 2(1 - r^2)^2/[(r^2 + 1)^2 r^2] \). Using Eqs. (11)–(16), \( \Delta \delta_{u, \kappa} \) can be written as
\[
\Delta \delta_{u,T} = \frac{3}{2} \sin^{-1} \left[ \frac{k^2}{2} \sqrt{1 + \frac{1}{r(2 - \kappa^2)}} \right], \tag{18}
\]
\[
\Delta \delta_{u,R} = \frac{4}{3} \sin^{-1} \left[ \frac{k^2}{2} \sqrt{\frac{1}{r(2 + r\sqrt{2 - \kappa^2})}} \right].
\]
Note that values of \( \kappa_1 \) and \( r_1 \) for Eqs. (17) and (18) can be found via Eq. (16). Using Eqs. (17) and (18), we have plotted \( \gamma_{y,\kappa} \) and \( \Delta \delta_{u, \kappa} \) of the flat-band SL in Fig. 6. The DBPs are shown in the inset in Fig. 6. Using Fig. 6, tunable flat-band SL can be realized by tuning the coupling coefficients \( \kappa \) and \( \kappa_1 \). Active tunability of \( \kappa \) and \( \kappa_1 \) is possible by using microelectromechanical systems [22] or other active tuning schemes [23], while passive tunability of \( \kappa \) and \( \kappa_1 \) (useful when it is complicated and/or costly to realize active devices) can be achieved.
by designing different lithography masks. Some general points with regard to Fig. 6 are summarized below.

Firstly, for both ports, \( \kappa_{gm,q} \) and \( \Delta \delta_{u,q} \) share an inverse relationship: \( \kappa_{gm,q} \) increases with decreasing \( \kappa \), while \( \Delta \delta_{u,q} \) increases with increasing \( \kappa \). Thus, a trade-off exists between \( \kappa_{gm,q} \) and \( \Delta \delta_{u,q} \). One needs to decide whether a large \( \kappa_{gm,q} \) or \( \Delta \delta_{u,q} \) is needed for the intended SL applications, as it is not possible to achieve both. Secondly, the DBP of the through (reflection) port stays rather constant at \( \sim 0.6 \) (\( \sim 1.3 \)). This matches closely with our earlier deduction of DBP = \( 2/\pi \) (DBP = \( 4/\pi \)) for the through (reflection) port. A rather constant DBP results in the above-mentioned inverse relationship between \( \kappa_{gm,q} \) and \( \Delta \delta_{u,q} \).

The actual group delay \( t_{gm} \) and actual usable bandwidth \( \Delta f_u \) depend on the cavity length \( L_c \) and the coupling values \( \kappa \) and \( \kappa_1 \). For a circular microring resonator (MRR) that has \( L_c = 2\pi R \) (\( R \) is the bend radius) and is based on silicon-on-insulator (SOI) channel WG with width and height of 0.5 \( \mu \)m, using \( (\kappa, \kappa_1) = (0.3, 0.0195) \) in Fig. 6 at \( R = 6 \mu \)m will translate into flat-band SL with \( t_{gm} = 46 \) ps and \( \Delta f_u = 10 \) GHz at the reflection port, while using \( (\kappa, \kappa_1) = (0.5, 0.0594) \) in Fig. 6 will give SL with \( t_{gm} = 16 \) ps and \( \Delta f_u = 26 \) GHz at the same port and \( R \). Thus, the actual group delay (bandwidth) decreases (increases) with \( \kappa \). However, if a smaller \( R \) of 2 \( \mu \)m is used for the above MRR, \( (\kappa, \kappa_1) = (0.5, 0.0594) \) in Fig. 6 will translate into flat-band SL with \( t_{gm} = 6 \) ps and \( \Delta f_u = 78 \) GHz at

### Table 1. Comparison of the DBPs Between Different Traveling-Wave MR-based SL Schemes

<table>
<thead>
<tr>
<th>Conventional MR-based systems of ( N )-cavities or unit cells in literature</th>
<th>This work</th>
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<tbody>
<tr>
<td><strong>System A:</strong> N-cavities-1-bus configuration (^{a})</td>
<td>( \leq 2/\pi )</td>
</tr>
<tr>
<td><strong>System B:</strong> N-cavities-2-buses configuration (^{b})</td>
<td>( \leq 1/(2\pi) )</td>
</tr>
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<td><strong>System C:</strong> Coupled-resonator-induced transparency-based scheme ([8-11,17,18])</td>
<td>( \leq 1/\pi )</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Output light at through port</th>
<th>Output light at reflection port</th>
</tr>
</thead>
<tbody>
<tr>
<td>Improvement of 3-fold, 12-fold, and 6-fold, as compared, respectively, to the DBPs of systems A, B, and C.</td>
<td>Improvement of 4-fold, 24-fold, and 12-fold, as compared, respectively, to the DBPs of systems A, B, and C.</td>
</tr>
</tbody>
</table>

\( \approx 0.212 \) \( \approx 0.0531 \) \( \approx 0.106 \)

\(^{a}\)N-cavities-1-bus configuration: a chain of \( N \)-resonators coupled to one bus WG. This is also known as the all-pass filter configuration if all the cavities are lossless.

\(^{b}\)N-cavities-2-buses configuration: a chain of \( N \)-resonators coupled to two bus WGs. This is also known as the add-drop filter configuration. Note that \( N(= 1, 2, 3, \ldots) \) is the number of resonators.
the reflection port. Thus, a smaller $R$ gives a larger $\Delta f_u$ but at a trade-off of a smaller $t_{gm}$. A compromise must therefore be reached depending on whether a large $\Delta f_u$ or $t_{gm}$ is needed. Note that if a racetrack MRR is used instead of a circular MRR, $t_{gm}$ will be larger albeit a smaller $\Delta f_u$. We will thus focus on circular MRRs for the rest of this work.

5. EFFECTS OF FABRICATION ERRORS AND CAVITY LOSSES

The performances of our proposed device after fabrication will chiefly depend on (1) the fabrication tolerance and (2) the cavity losses. It is found that the flat-band SL of our device is relatively unaffected if fabrication errors in the WG and cavity dimensions are about $\pm 1\%$. To date, deep UV lithography has made it possible to control the WG dimensions to within $\pm 1\%$ [24] for SOI-based MRRs. Hence, fabrication tolerance is not much of an issue for our proposed scheme. On the other hand, cavity losses, which consist of the propagation and coupler losses, are expected to be the dominant sources of degradation to the SL performances of our proposed device. These are discussed below.

A. Propagation Losses

In MRRs, the chief components of the propagation losses are the fabrication-induced sidewall roughness losses and the bend losses. The bend losses are the main source of the propagation losses, as the fabrication-induced sidewall roughness

![Figure 6](image1.png)

**Fig. 6.** (Color online) The normalized group delay (left axis) and the normalized usable resonance bandwidth (right axis) of the flat-band SL for the through port (solid curves) and reflection port (dotted curves) of the proposed device at different $\kappa$. Corresponding values of $\kappa_1$ can be found in Fig. 4. The inset shows the DBP.

![Figure 7](image2.png)

**Fig. 7.** (Color online) The effects of cavity losses on the transmission $T_q$ and group delay $t_{g,q}$ spectra of the flat-band SL at the (a)–(aii) through port and the (b)–(bii) reflection port of the proposed device with $(\kappa, \kappa_1) = (0.3, 0.0471)$ for the through port and $(\kappa, \kappa_1) = (0.3, 0.0195)$ for the reflection port.
can easily be reduced to a negligible level [25]. The propagation losses of each MRR are quantified by \( \tau_n \). As \( \delta_1 = \delta_2 = \delta \) in this work, we use \( \tau_1 = \tau_2 = \tau \) (\( \tau < 1 \), net optical loss; \( \tau = 1 \), zero optical loss).

Let us first look at the effects of varying \( \tau \) (assuming no coupling loss) on the flat-band SL for one particular example of \( \kappa = 0.3 \) for our proposed device (with value of \( \kappa_1 \) from Fig. 4). It can be seen in Fig. 7 that flat-band SL with close to unity transmission \( (T_{q} = 1) \) can be realized at both ports provided that \( 0.9999 \leq \tau \leq 1 \). For such small losses of \( 0.9999 \leq \tau \leq 1 \), the group delay of the flat-band region (at \( \delta = 2\pi m \)) of the flat-band region is rather independent of \( \tau \). Increasing the losses to \( \tau < 0.9999 \) results in the transmission falling considerably below \( T_{q} = 1 \), while the group delay remains fairly unaffected as long as \( \tau \) does not fall considerably below \( \tau < 0.9999 \). To relax the fabrication constraints, we will consider devices with transmissions of \( 0.8 \leq T_{q} \leq 1 \).

The general characteristics as seen in Fig. 7 apply to any value of \( \kappa \). However, the range of values of \( \tau \) that gives flat-band SL changes with \( \kappa \). To illustrate this, we have shown the transmission \( T_{q} \) and group delay responses at \( \delta = 2\pi m \) of our device as a function of \( \tau \) for different \( \kappa \) (with values of \( \kappa_1 \) from Fig. 4) in Fig. 8. It can be observed that there are specific values of \( \tau \) that give points of asymptote in the group delay responses, with corresponding points of \( T_{q} = 0 \) in the transmission responses. This phenomenon of \( T_{q} = 0 \) that is accompanied by a sharp change in the group delay for resonator systems is generally known as critical coupling. We will term the values of \( \tau \) that give such phenomenon as \( \tau_c \). The value of \( \tau_c \) (cf. points of asymptote and \( T_{q} = 0 \) in Fig. 8) decreases with increasing \( \kappa \). As a result, the transmission \( T_{q} \) and group delay near the points corresponding to \( T_{q} = 1 \) become less sensitive to changes in \( \tau \) at large \( \kappa \). Generally, the group delay is less sensitive to changes in \( \tau \) than the transmission, consistent with Fig. 7. For both the through and reflection ports, the group delay is fairly constant (cf. insets in Fig. 8(aii) and 8(biii)) for all \( \tau \) if \( \tau \) is in the range of \( 0.98 \leq \tau \leq 1 \). On the other hand, to have high transmission of \( 0.8 \leq T_{q} \leq 1 \) (cf. insets in Fig. 8(ai) and 8(bi)) for both ports and all \( \kappa \), the allowed range of \( \tau \) reduces to \( \sim 0.9999 \leq \tau \leq 1 \).

Theoretically speaking, it is possible to achieve the above range of \( \sim 0.9999 \leq \tau \leq 1 \) for a passive MRR with bend radius \( R \) of \( R \geq 2 \) \( \mu m \) of SOI wires are used [26]. Moreover, it has been experimentally demonstrated that \( \tau = 0.9999 \) can be achieved for a passive SOI-based MRR with \( R = 1.0 \) \( \mu m \) [27]. This implies the technical possibility to realize \( \sim 0.9999 \leq \tau \leq 1 \) for an SOI-based MRR with \( R \geq 2 \) \( \mu m \) as \( \tau \) increases exponentially with \( R \).

The effects of varying \( \sigma \) on the flat-band SL of the proposed device is shown in Fig. 9 for the case of \( \kappa = 0.3 \) (with values of \( \kappa_1 \) from Fig. 4). It is evident that for the through (reflection) port, a coupler loss of \( \sigma \leq -0.04 \) \((\sigma \leq -0.02)\) at each CJ will keep the transmission of the flat-band SL (at \( \delta = 2\pi m \)) to a high level of \( 0.8 \leq T_{q} \leq 1 \). The group delay at \( \delta = 2\pi m \), on the other hand, is relatively independent of the coupler losses.

The general characteristics as seen in Fig. 9 apply to any value of \( \kappa \). However, the range of values of \( \tau \) that gives flat-band SL changes with \( \kappa \). To illustrate this, we have shown the transmission \( T_{q} \) and group delay responses at \( \delta = 2\pi m \) of our device as a function of \( \tau \) for different \( \kappa \) (with values of \( \kappa_1 \) from Fig. 4) in Fig. 10. It can be seen from Figs. 10(ai) and 10(bi) that, for each value of \( \kappa \), the transmission \( T_{q} \) decreases...
with increasing $\sigma$ until the critical coupling point (in which $T_q = 0$) is reached. We will term the value of $\sigma$ that gives critical coupling as $\sigma_c$. Such a critical coupling point is reflected as an asymptote in the group delay spectra in Figs. 10(aii) and 10(bii). In general, $\sigma_c$ increases with $\kappa$. Consequently, the transmission $T_q$ and group delay near the points corresponding to $T_q = 1$ become less sensitive to changes in $\sigma$ at larger $\kappa$. Also, as shown in Fig. 10, the group delay is less sensitive to changes in $\sigma$ than the transmission. For both the through and reflection ports, the group delay is fairly constant for all $\kappa$ provided that $\sigma \leq 0.1$. However, to achieve flat-band SL with high transmission of $0.8 \leq T_q \leq 1$ for both ports, the allowed range of $\sigma$ will decrease to $\sigma \leq 0.02$ so that all values of $\kappa$ can be utilized.

It is found that for an SOI-based circular MRR, $\sigma$ at each CJ is $\sigma < 0.01$ for bend radius $R \geq 1 \mu m$ [27]. This implies that the effects of coupler losses on the flat-band SL of our device are negligible as $\sigma \leq 0.02$ for our proposed scheme, as mentioned above. Based on the results in Subsections 5.A and 5.B, we can conclude that our proposed scheme is suitable for practical SL applications when a circular SOI-based MRR is being used.

Finally, note that the fact that the ranges of $-0.999 \leq \tau \leq 1$ (cf. Subsection 5.A) and $\sigma \leq 0.02$ (this section) give flat-band
SL with high transmission does not conflict with the well-known Kramers–Kronig relation [2]. As mentioned in [28], for MR structures, the Kramers–Kronig relation exists only in the under-coupling regime. However, the above-mentioned ranges of $-0.999 \leq \tau \leq 1$ and $\tau \leq -0.02$ will cause our proposed MR structure to be in the over-coupling regime. This produces SL [6], which has been demonstrated in this work.

6. SUMMARY AND CONCLUSIONS

We have proposed a twin coupled traveling-wave MRs scheme to generate flat-band SL at both the through and reflection ports. Such flat-band SL has (1) maximally flat transmission spectrum, (2) high transmission, (3) minimal GDD, (4) enhanced DBPs that are 3- to 24-fold (cf. Table 1) higher than conventional SL systems [3–6,8–18], and (5) tunable bandwidth and group delay (by adjusting the coupling coefficients). It is also found that the fabrication errors in the WG dimensions must be kept within $\pm 1\%$ and that the size of the bend radius $R$ should be $R \geq 2 \mu m$ so that the flat-band SL is not severely degraded. These can be achieved as advancement in fabrication technology has allowed a fabrication tolerance of $\pm 1\%$ [24] and low-loss MRs with $R$ as small as 1 $\mu m$ [27] to be fabricated. Our proposed device will, therefore, be suitable for practical SL applications.

REFERENCES