PROCEEDINGS OF SPIE

SPIEDigitalLibrary.org/conference-proceedings-of-spie

Coupled resonator optical waveguides (CROW)

Jacob Scheuer, Joyce K. S. Poon, George T. Paloczi, Amnon Yariv

Jacob Scheuer, Joyce K. S. Poon, George T. Paloczi, Amnon Yariv, "Coupled resonator optical waveguides (CROW)," Proc. SPIE 5735, Advanced Optical and Quantum Memories and Computing II, (4 April 2005); doi: 10.1117/12.602589

SPIE.

Event: Integrated Optoelectronic Devices 2005, 2005, San Jose, California, United States

Coupled Resonator Optical Waveguides (CROWs)

Jacob Scheuer*[a], Joyce K. S. Poon[b], George T. Paloczi[c] and Amnon Yariv[b,c]
[a] Center for the Physics of Information, California Inst. of Technology, 1200 E. California Blvd., Pasadena, CA USA 91125
[b] Dept. of Electrical Engineering, California Inst. of Technology, 1200 E. California Blvd., Pasadena, CA USA 91125
[c] Dept. of Applied Physics, California Inst. of Technology, 1200 E. California Blvd., Pasadena, CA USA 91125

ABSTRACT

We investigate theoretically and experimentally the characteristics, performance and possible applications of coupled resonator optical waveguides (CROWs). The ability to engineer the dispersion properties of a CROW and especially the ability to realize ultra-slow group velocities paves the way for various applications such as delay lines, optical memories and all-optical switching. Simple analytic expressions for the time delay, usable bandwidth and overall losses in CROW delay lines are derived and compared to exact numerical simulation. Good quantitative agreement is found between the theoretical transmission function obtained by transfer matrix formalism and the measurement of a CROW interferometer realized in polymer material.
Keywords:

1. INTRODUCTION

A chain of coupled resonators is a new type of waveguide in which light propagates due to the coupling between adjacent resonators. Such waveguides, called coupled resonators optical waveguides (CROWs), offer improved control over their dispersion characteristics (compared to conventional waveguide) and may potentially find applications in delaying, storing and buffering of optical pulses.[1-3]

A CROW can be realized with various types of resonators such as Fabry-Perot (FP), photonic crystal (PC) defect cavities and ring resonators.[4-6] Although these implementations differ in the fine details such as the confinement and coupling mechanisms, the general characteristics (dispersion relation, band structure, etc.) are very similar and are determined primarily by the free spectral range (FSR), the quality-factor (Q) of each resonator, and the coupling between adjacent resonators.[7]

In addition to different resonator types, coupled cavity waveguides (CCW) can employ alternative coupling configurations such as the single, double and twisted side-coupled integrated sequences of optical resonators (SCISSOR).[3,8] The various coupling schemes are characterized by different feedback configuration, and hence, exhibit different spectral responses and dispersion curves. Depending on the resonator type used, not all the coupling configurations can be easily realized. FP and one-dimensional PC defect cavities introduce an inherent distributed feedback to the system, and are therefore, unsuitable for the realization of all-pass type CCWs such as the single side and twisted SCISSOR.[8]

* koby@caltech.edu; phone 1 626 395-4413; fax 1 626 405-0928; www.its.caltech.edu/~koby/

Advanced Optical and Quantum Memories and Computing II, edited by Hans J. Coufal, Zameer U. Hasan, Alan E. Craig, Proceedings of SPIE Vol. 5735
(SPIE, Bellingham, WA, 2005) · 0277-786X/05/$15 · doi: 10.1117/12.602589

In this paper we focus primarily on directly coupled resonators waveguides (i.e.. CROWs). In particular, we are interested in CROWs implemented in ring resonators (see Fig. 1). Single mode, high Q ($>10^6$), planar-technology based microrings are being fabricated by many research groups as well as by several commercial companies.[9] The realization of microrings is simple, requires a single fabrication step and does not require ultra-high resolution lithography.[10] In section 2 we describe theoretical framework used to analyze CROWs and derive the CROW dispersion curve, bandwidth and losses. In section 3 we focus on a specific and highly attractive application for CROWs, an optical delay line, and investigate the tradeoffs among the achievable delay, bandwidth and losses. In section 4 we report the experimental progress in the realization of CROWs and CROW interferometers in optical polymer material and in section 5 we conclude.

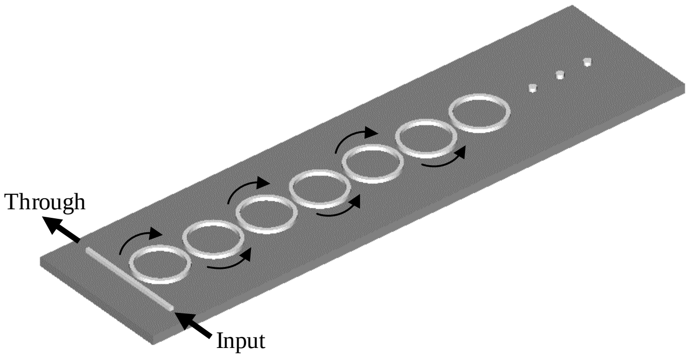

Figure 1. An illustration of a CROW.

2. THEORETICAL FRAMEWORK

We consider a chain of directly coupled ring resonators as shown in Fig. 2. The leftmost and rightmost resonators are coupled to linear waveguides which serve as I/O ports. While the spectral properties of a finite chain of resonators differ from those of an infinite chain, for a large number of resonators, the finite device can be approximated by an infinite one. A CROW can be analyzed in various frameworks such as the tight-binding method, transfer matrices and time domain analysis. Among these frameworks, the transfer matrix method is the most intuitive and flexible because it naturally allows for the analysis of finite, lossy and dispersive structures with strong coupling coefficients that are not necessarily identical for all resonators. Nevertheless, it has been shown that the results of all frameworks converge for lossless, weakly coupled resonators.[7]

An infinite chain of resonators is a periodical structure which supports Bloch waves.[11] For ring resonators, a special and important wave that can be excited is one in which each resonator supports a clockwise or counterclockwise propagating wave where the light in adjacent resonators circulates in opposite directions (see Fig. 2). This wave is not a Bloch wave because it does not satisfy the Bloch condition, $u_n=\exp(iK\Lambda)\cdot u_{n-1}$. It is formed by a superposition of two degenerate Bloch modes consisting of standing waves in each resonator.

One can calculate the transmission of a CROW by successively multiplying the transfer matrix characterizing the relation between two adjacent resonators.[12] This matrix consists of two stages: 1) coupling ($x_n \rightarrow x'_n$) and 2) propagation ($x'_n \rightarrow x_{n+1}$), where x is a vector of the wave amplitudes, $x=(a \quad b)^T$, as shown in Fig. 2. The relation between the field amplitudes of successive rings is given by:

$$\begin{pmatrix} a \\ b \end{pmatrix}_{n+1} = PQ\begin{pmatrix} a \\ b \end{pmatrix}_n, \qquad P=\frac{1}{\kappa}\begin{pmatrix} -t & 1 \\ -1 & t^* \end{pmatrix}, \qquad Q=\begin{pmatrix} 0 & \exp(-i\pi\beta R) \\ \exp(i\pi\beta R) & 0 \end{pmatrix} \tag{1}$$

where t and κ are respectively the transmission and coupling coefficients satisfying $|t|^2+|\kappa|^2=1$, β is the propagation coefficient in the ring and R is the ring radius. The transfer matrix between adjacent resonators (1) can be used to calculate the dispersion relation of the CROW. Noting that the traveling wave solution is periodic it 2Λ (Λ being the periodicity of the CROW and is given approximately by the ring diameter $2R$), the dispersion relation of the CROW is found by requiring the Bloch condition with a unit cell consisting of two successive resonators:

$$\left[(PQ)^2 - \exp(i2K\Lambda)\right]x_n = 0 \qquad (2)$$

where K is the Bloch wave vector. For a nonzero solution the determinant of the matrix must vanish leading to the dispersion relation:

$$\sin\left(\frac{\omega_K}{\Omega} m\pi\right) = \pm \operatorname{Im}(\kappa)\cos(K\Lambda) \qquad (3)$$

where ω_K is the angular frequency corresponding to K, Ω is the resonance frequency of the individual resonator and $m=\Omega nR/c$, n being the frequency dependent effective index of the waveguide composing the ring resonator. In the limit of small coupling, $|\kappa|<<1$, the dispersion relation reduces to the expression found by the tight-binding approach[1]:

$$\omega_K = \Omega\left[1 \pm \frac{|\kappa|}{m\pi}\cos(K\Lambda)\right] \qquad (4)$$

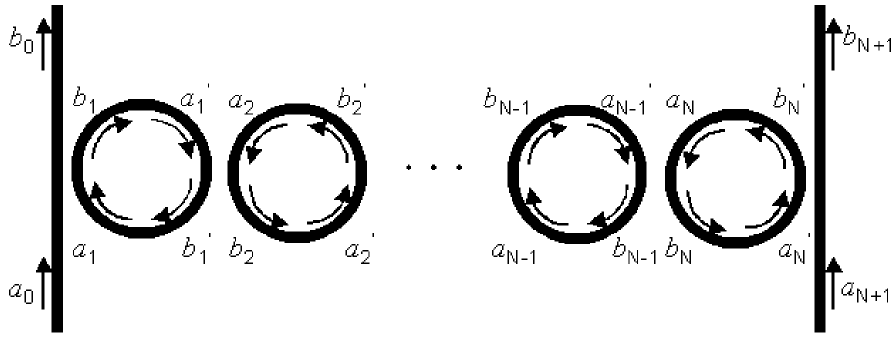

Figure 2. Traveling wave in a finite CROW.

One of the main advantages of the transfer matrix method is its ability to describe finite and lossy structures. Loss can be incorporated simply by adding an imaginary term to the propagation coefficient β. For finite structures, one can derive a transfer matrix connecting the amplitudes of the waves in the I/O waveguides coupled to the CROW (see Fig. 2):

$$\begin{pmatrix} a \\ b \end{pmatrix}_{N+1} = \begin{pmatrix} A & B \\ C & D \end{pmatrix}\begin{pmatrix} a \\ b \end{pmatrix}_0 \qquad (5)$$

Given the inputs to the CROW, a_0 and a_{N+1}, the outputs b_0 and b_{N+1} can be readily evaluated from (5). For a single input (e.g. $a_{N+1}=0$), the transmission functions of the through (b_0) and drop (b_{N+1}) ports are given by:

$$\frac{b_0}{a_0} = -\frac{A}{B}, \qquad \frac{b_{N+1}}{a_0} = C - \frac{AD}{B} \qquad (6)$$

Figure 3 depicts a comparison between the dispersion relation of an infinite CROW and a finite device consisting of 20 resonators with coupling coefficient of $|\kappa|^2=0.5$, $R=20\mu$m and $n=1.5$. The small ripples in the transfer function of the finite CROW stem from the resonances of the structure. As the number of resonators is increased, these resonances will be infinitely close and the ripples will be smoothed out. For the finite structure the wave vector is derived from the average phase shift between adjacent resonator given by the ratio between the device phase response and the number of resonators. There is an excellent agreement between the dispersion relations except for frequencies that are close to the band edge. This deviation stems from the fact that the separation between the pass-band and the bandgap is clearly defined only for an infinitely long structure. For a finite structure there is a smooth transition between them which manifests in the deviation between the dispersion curves in the transition region.

3. CROW DELAY-LINE: PERFORMANCE AND TRADEOFFS

3.1. Delay, Usable Bandwidth and Loss

The dispersion relation (3) can be used to derive the propagation velocity of a pulse in the CROW (i.e., the group velocity):

$$|v_g| = \left|\frac{d\omega_K}{dK}\right| = \frac{|\kappa|\Lambda\Omega}{m\pi}\cdot\frac{\sin(K\Lambda)}{\sqrt{1-|\kappa|^2\sin^2(K\Lambda)}} \quad (7)$$

The group velocity is maximal at the center of the pass-band ($\omega_K = \Omega$) and is equal to:

$$|v_g|_{\max} = \frac{|\kappa|\Lambda\Omega}{m\pi}\bigg/\sqrt{1-|\kappa|^2} \quad (8)$$

The minimal group velocity approaches zero close to the edges of the pass-band (see Fig. 3). However, the dependence of v_g of the frequency or the group velocity dispersion (GVD) at the band-edge is very strong. The immediate consequence is that a pulse propagating in that spectral region is severely distorted. On the other hand, the GVD and, therefore, the distortion at the center of the pass-band (at the resonance of the individual resonators) are minimal but the group velocity is maximal.

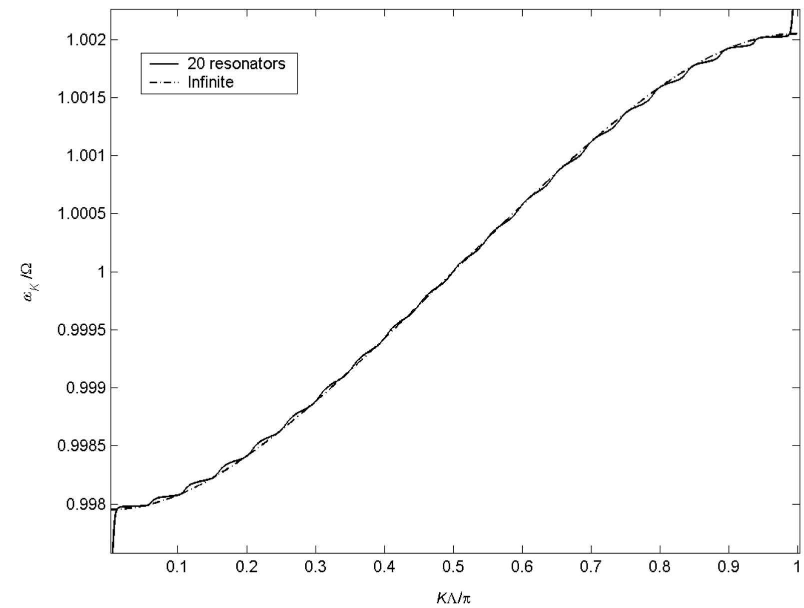

Figure 3. Exact dispersion relations for a 20 resonator (solid) and an infinite (dash-dot) CROWs.

Although maximal within the pass-band, the group velocity can be decreased almost arbitrarily by increasing the perimeter of each resonator in the CROW and reducing the coupling between the resonators. Intuitively, the impact of these parameters on the group velocity is as follows: Reducing the coupling coefficient between adjacent resonators increases the time it takes for the light to tunnel from one resonator to its neighbor. Increasing the perimeter, which is equivalent to elongating the optical path in the resonator, increases the roundtrip time. Both actions effectively prolong the time the pulse "spends" in each resonator, giving rise to a slower propagation velocity. It should be noted that if the resonators are perfect rings, increasing the perimeter does not result in a smaller group velocity because the inter-cavity periodicity Λ is also increased. For racetrack resonator, however, it is possible to increase the resonators perimeter without increasing Λ, and hence, decrease the group velocity.

The significant slowing down of light that can be achieved by reducing the FSR and κ is not accomplished without drawbacks. Reducing the coupling (or increasing the radius) decreases the available bandwidth of the pass-band (see figure 1). A smaller coupling ratio implies that the light circulates longer in each resonator and thus a stricter tolerance is imposed on the deviation of the optical frequency from the resonance frequencies of the resonators. In addition to reducing the usable bandwidth, reducing the coupling (or the FSR) may increase the overall loss in the CROW. In an ideal CROW, consisting of loss-less resonators, light propagates without loss regardless the number of resonators and the coupling between them. Passive resonators, on the other hand, have losses due to surface scattering, material absorption and waveguide-bending radiation. The more times light circulates in each resonator the larger the loss experienced by the pulse as it propagates along the CROW.

From (3), the pass-band of the CROW spans the frequency range $\Delta\omega = 2\Omega\sin^{-1}(|\kappa|)/m\pi$. Because of GVD, we define the usable bandwidth of a CROW as half of this bandwidth:

$$\Delta\omega_{use} = \frac{\sin^{-1}(|\kappa|)c}{\pi n R} \underset{\kappa<<1}{\approx} \frac{|\kappa| c}{\pi n R} \tag{9}$$

where the CROW periodicity, Λ, is taken to be approximately $2R$. The overall delay of a pulse propagating along the CROW is given by the ratio between the CROW length and the group velocity at frequency Ω:

$$\tau \underset{\kappa<<1}{\approx} \frac{\pi n RN}{|\kappa| c} \tag{10}$$

where N is the number of resonators in the CROW. Thus, the CROW acts as a conventional waveguide with group index n but with an effective length of $L_{eff} = \pi RN/|\kappa|$, i.e., $1/2|\kappa|$ times longer than the length of the waveguides composing the N resonators. Hence, the loss experienced by a pulse propagating from the CROW input to output can be approximated by the product of L_{eff} and the loss per unit length in the waveguide:

$$\alpha = \frac{a\pi RN}{|\kappa|} \tag{11}$$

where a is the loss per unit length and $\exp(-\alpha)$ is the net power attenuation of the CROW.

Equations (9)-(11) summarize the connections and tradeoffs among the primary characteristics of a CROW delay line. Although the derivation of these simple relations was based primarily on intuition, it has been shown that they agree very well with the exact, numerically calculated, delay, bandwidth and loss for a wide range of parameters.[7] The product of the usable bandwidth and the achievable delay is the number of resonators, N. Thus, for a given desired bandwidth, the delay can be increased simply by adding more resonators to the CROW. Unfortunately, the overall transmission losses of the CROW increase linearly with N and is proportional to the delay – $\alpha = a\tau c/n$. The last expression for the loss coefficient is intuitively understood as the product between the time delay and the loss per unit time which is given by ac/n. Fundamentally, the performance of a CROW delay line are limited primarily by the loss in the individual resonators, i.e., the intrinsic quality factor (Q_{int}). For a given maximal acceptable loss $L=1-\exp(-\alpha_{max})$, the maximal achievable delay is independent of the coupling and given by:

$$\tau_{nax} = \frac{n\alpha_{max}}{ac} \tag{12}$$

Figure 4 illustrates these design tradeoffs for a CROW consisting of 10 coupled ring resonators having a FSR of 310 GHz and propagation loss of 4 dB/cm. The markers show exact results computed numerically while the lines are the analytic approximations. To achieve a long delay, a small coupling is desired, which decreases the bandwidth of the CROW, and the overall loss of the CROW becomes more sensitive to the intrinsic loss in the individual resonator. As a result the limiting factor of the bandwidth-delay product is the acceptable loss of the delay line and achieving long delays requires resonators with high Qs.

3.2. Figure of Merit

The simple relations derived in section 3.1 demonstrate that for a given technology (i.e. resonator type, losses, dimensions, etc.) the optimization of the various attributes is mutually contradictory and that one of the desired properties can be improved only at the expense of another. In addition, different technologies and resonator types may favor some properties over others. Therefore, it is necessary to define a figure of merit (FOM) which reflects the tradeoffs among the CROW properties and can be used to compare different realizations of CROW delay lines. It is clear that the main attribute that limits the usable bandwidth and the achievable delay is the loss in the individual resonator.

More precisely, the important factor is the ratio between the photon cavity lifetime due to coupling to the adjacent resonator and the lifetime due to internal loss or, equivalently, the ratio between the external and intrinsic *Q*s.

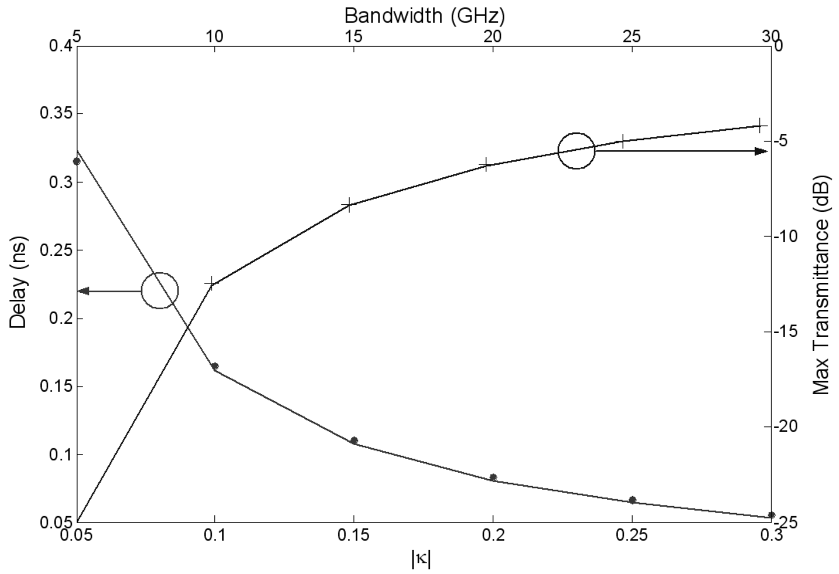

Figure 4. Tradeoffs among delay, losses and bandwidth for a CROW consisting of 10 coupled ring resonators having a FSR of 310 GHz and propagation loss of 4 dB/cm.

For a CROW delay line to be useful, the external *Q* should be significantly smaller than the intrinsic *Q* or, equivalently, $T_{ext} << T_{int}$. This condition implies that the time it takes the light to propagate from cavity to cavity is much smaller than the intrinsic photon lifetime in each cavity. We therefore define an FOM for CROW delay lines as:

$$\text{FOM} = T_{int} / T_{ext} \quad (13)$$

The external time constant is equal to the time the light takes to propagate through a single resonator in the CROW, i.e., $T_{ext} = \Lambda/|v_g|_{max} = m\pi/|\kappa|\Omega$. The internal time constant is given by $T_{int} = n/ac$ so the FOM can be expressed as:

$$\text{FOM} = \frac{|\kappa|}{a\pi R} = \frac{\Delta\omega_{use}\tau}{\alpha} \quad (14)$$

Equation (14) reveals that the FOM also represents the balance between the loss, bandwidth and delay of the CROW. It is important to note that the main parameter which limits the performance of a CROW delay line is the losses, or internal photon lifetime, of the individual cavities. The lower the cavity losses, the better a delay line can be constructed. It should be emphasized, however, that the FOM (14) takes into account only the performance issue and that other practical considerations such as fabrication complexity, repeatability and yield are not considered.

4. EXPERIMENTAL PROGRESS

The main characteristics of a CROW are expressed by the phase response of the device. Figure 5a depicts a Mach-Zehnder interferometer (MZI) where one of the arms consists of a micro-ring based CROW.[13] Such a device enables the study of the wavelength dependent phase characteristics (i.e., the dispersion) of the CROW which determine the delay. The waveguides, consisting of SU-8 cores, are written directly on thermally grown silicon-oxide lower-cladding using electron beam lithography. The dimensions of the waveguides are 1.6μm X 2.0μm, the circumference of the resonators is ~730μm yielding an FSR of ~2.2nm.

In Figure 5b we show the theoretical fit (dashed), based on the transfer matrices formalism, of the CROW-MZI transmission superimposed on the experimental data (solid) of the power transmission of the device. According to the fit, the average delay of the device is ~4 ps and the loss is ~3 dB per resonator. Although the loss characteristics may seem somewhat deterring, if improvements in the waveguides are made (loss of ~1dB/cm), one can obtain a significantly reduced loss of ~0.1 dB/resonator. It should be emphasized that the unique characteristics of a CROW (dispersion curve, group delay, usable bandwidth, etc.) can only be attributed to a device consisting of a large number of resonators. Figure 5c depicts an optical image of such device, comprising 25 coupled resonators.

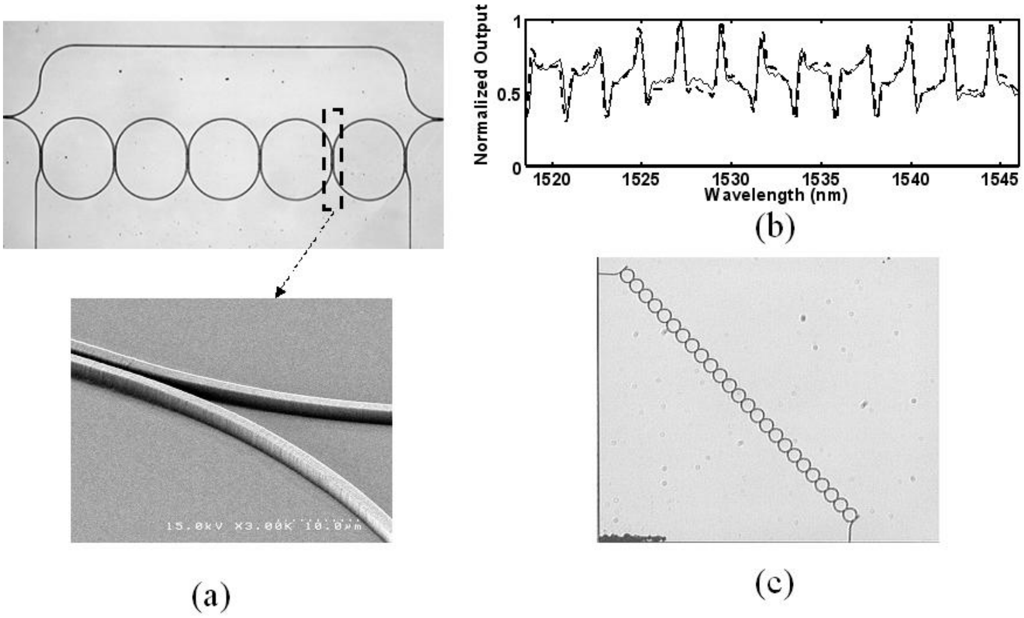

Figure 5. a) An optical micrograph of the CROW-MZI and an SEM zoom on the coupling region; b) A theoretical fit (dashed) and a measurement (solid) of the CROW-MZI transmission. The fit parameters are κ=0.46 and loss of 30dB/cm; c) a CROW consisting of 25 resonators.

For the measurement, a tunable laser diode provided TE-polarized (electric field parallel to the layer structure) optical signal input via a polarization controller and a tapered single-mode fiber. The output spectrum shown in Fig. 5b is the interference pattern of the CROW drop port (6) and the output of a standard waveguide:

$$\text{Output} \propto \left| C\text{-}\frac{AD}{B} + \exp\left[\left(-a + i\beta\right)L_{\text{MZI}}\right]\right|^2 \qquad (15)$$

where a and β are respectively the loss and propagation coefficient of the waveguide and L_{MZI} is the length of the upper arm (see Fig. 5a) of the interferometer.

6. CONCLUSIONS

We have studied the key issues in the design of CROWs, especially for the application of optical delay lines. We have derived simple analytic expressions for the main characteristics of such delay line: achievable delay, usable bandwidth and transmission loss and a figure of merit which facilitates the comparison among different CROW delay lines. These expressions offer a simple and practical tool to evaluate the feasibility of and approximate design parameters for a CROW delay line. The coupled resonator waveguide concept offers a pathway towards the realization of slow propagating light in practical systems. With the currently available state-of-the-art waveguide technology, it is possible to realized substantial delays with reasonable loss and bandwidth.

ACKNOWLEDGMENTS

This research was supported by Defense Advanced Research Projects Agency and the Air Force Office for Scientific Research.

REFERENCES

1. A. Yariv, Y. Xu. R. K. Lee and A. Scherer, "Coupled resonator optical waveguides: a proposal and analysis", Opt. Lett. **24**, 711-713, 1999.
2. N. Stefanou and A. Modinos, "Impurity bands in photonic insulators", Phys. Rev. B. **57**, 12127-12133, 1998.
3. A. Melloni and F. Morichetti, "Linear and nonlinear pulse propagation in coupled resonators slow-wave optical structures" Opt. And Quantum Electron. **37**, 525-532, 2001.
4. S. Lan, S. Nishikawa, H. Ishikawa ans O. Wada, "Design of impurity band-based photonic crystal waveguides and delay lines for ultrashort optical pulses", J. Appl. Phys. **90**, 4321-4327, 2001.
5. D. Leuenberger, R. Ferrini and R Houdré, "Annular Bragg Defect mode Resonators", J. Appl. Phys. **95**, 806-809, 2004.
6. J. K. S. Poon, J. Scheuer S. Mookherjea G.T. Paloczi, Y. Huang and A. Yariv, "Matrix analysis of microring coupled resonator optical waveguides", Opt. Express **11**, 2666-2671, 2003.
7. J. K. S. Poon, J. Scheuer, Y. Xu and A. Yariv, "Designing coupled-resonator optical waveguide delay lines", J. Opt. Soc. Am. B **21**, 1665-1673, 2004.
8. J. E. Hebner, P. Chak, S. Pereira, J. E. Sipe and R. W. Boyd, "Distributed and localized feedback in microresonator sequences for linear and nonlinear optics", J. Opt. Soc. Am. B **21**, 1665-1673, 2004.
9. K. J. Vahala, "Optical microcavities", Nature (London) **424**, 839-846, 2003.
10. Y. Huang, G. T. Paloczi, J. Scheuer and A. Yariv, "Soft lithography replication of polymeric microring optical resonators", Opt. Express **11**, 2452-2458, 2003.
11. A. Yariv, and P. Yeh, "*Optical Waves in Crystals: Propagation and Control of Laser Radiation*", Wiley, New York, 1984.
12. K. Oda N. Takato and H. Toba, "A Wide-FSR waveguide double ring resonator for optical FDM transmission systems", J. Lightwave Technol. **9**, 728-736, 1991.
13. G. T. Paloczi, Y. Huang, A. Yariv, and S. Mookherjea, "Polymeric Mach-Zehnder interferometer using serially coupled microring resonators", Opt. Express **11**, 2666-2671, 2003.