Observation of Pulse Compression in Photonic Crystal Coupled Cavity Waveguides

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***Abstract*—We demonstrate the compression of picosecond pulses using the large group velocity dispersion available from planar photonic crystal (PhC) coupled cavity waveguides (CCWs). A maximum pulsewidth reduction of 40%, from 1.91 to 1.17 ps, is achieved, in transmission through an 8-μm-long planar PhC waveguide. The equivalent dispersion value is $>10^6$ times larger than that available from standard single-mode fiber, at the pulse center wavelength of 1536 nm. The device performance is analyzed with the aid of both two-dimensional (2-D) eigenmode expansion and 2-D finite-difference time-domain (FDTD) models. The models included the material dispersion of the GaAs/AlGaAs heterostructure, into which the PhCs are etched, and show remarkable agreement with experiment.**

***Index Terms*—Band-gap structures, fabrication, optical planar waveguides, optical pulse compression.**

I. Introduction

PLANAR integration of two-dimensional (2-D) photonic crystals (PhCs) with conventional waveguides offers the potential of high-density integrated optics with significant functionality. The periodically modulated, strong refractive index contrast of the PhCs exhibits large spatial and temporal dispersion [1], offering a route to ultracompact component design. Of particular interest to optical communications are devices designed to operate in the 1300 and 1550 nm wavelength windows, where PhC filtering and dispersion compensation could impact upon future high-speed transmission systems. Such devices have previously been studied predominantly in terms of their CW transmission characteristics, whereas their dynamic performance has not yet been fully characterized. This paper demonstrates for the first time, to the author's knowledge, compression of pulses by transmission through 2-D PhCs. Critical problems such as out-of-plane losses and impedance mismatch remain to be resolved.

II. Device Concept and Design

Coupled cavity waveguides (CCWs) [2] are a subclass of PhC waveguides, a hybridization of line and point defects. The waveguiding mechanism uses the coupling between the eigenmodes of the individual cavities along a chain of adjacent cavities. Light is localized within the various normal modes of the chain, providing strong temporal dispersion. Such structures afford tailored group velocity dispersion in the construction of optical delay lines, filters, routers, pulse shapers, and dispersion compensators.

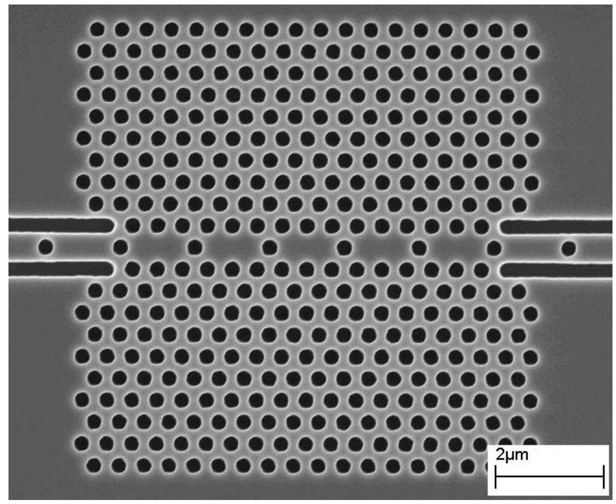

Fig. 1. Device under test, an L2in1 CCW, with lattice constant a $= 460$ nm. Coupling is facilitated via deeply etched trenches defining input/output ridge waveguides.

The dielectric configuration of the device under test is shown in Fig. 1. It consists of an L2in1 CCW, a line cavity with a unit cell comprising two missing holes with one spacer hole. Vertical confinement is provided by a GaAs/AlGaAs heterostructure. Devices are fabricated by electron beam lithography and reactive ion etching as in [3], although here the transfer of the SiO_2 mask into the semiconductor is facilitated using a chemically assisted ion beam etching (CAIBE) process, with Cl_2 as the reactive gas. This provides a deeper etch of 1.5 μm [as opposed to the 1 μm obtained previously using reactive ion etching (RIE)] promoting lower losses, by reducing the magnitude of the field component which can be scattered into the substrate. A set of six similar samples were prepared with small (8 nm) steps of lattice period in order to match the transmission band to that of the erbium doped fiber amplifier (EDFA) C-band, around 1550 nm. A constant filling factor was maintained, with a radius of $\mathrm{r} = 1/3\mathrm{a}$, where a is the lattice constant of the PhC.

III. Device Operation

Calculation of the photonic band structure of the unit cell, for TE polarization, was performed using the MIT Bands software

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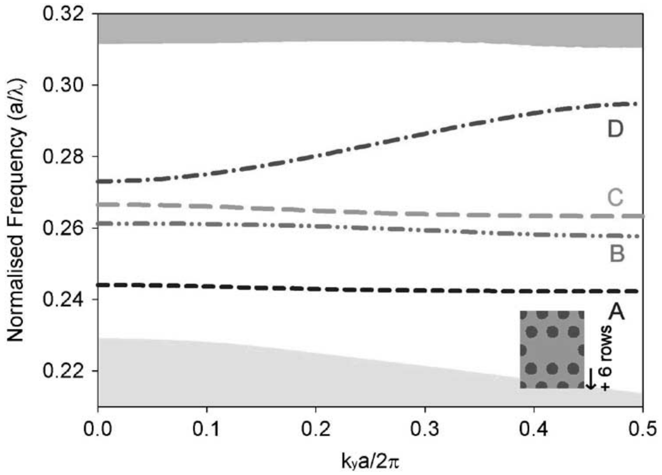

Fig. 2. Photonic bandstructure for infinite repetition of the inset super cell, four modes can be seen spanning the bandgap ($\mathrm{u} = 0.23$–0.31).

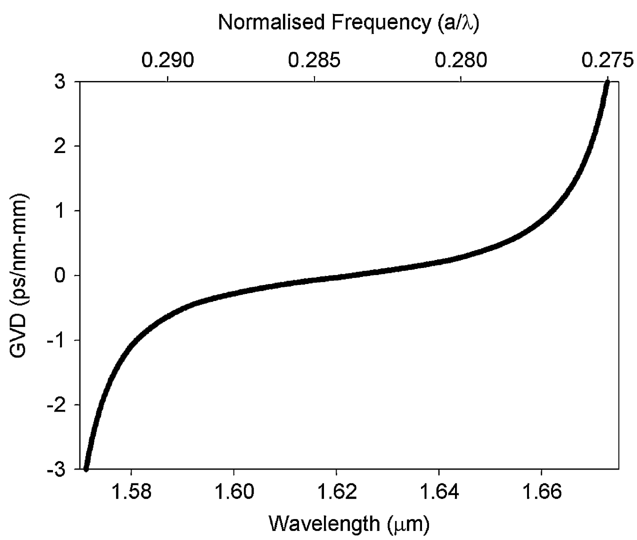

Fig. 3. GVD for mode D, calculated from above bandstructure.

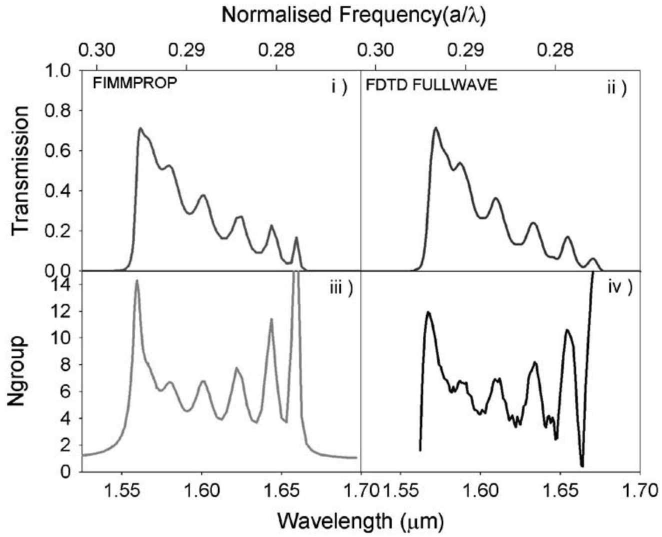

Fig. 4. Modeled transmission and group index from Fimmprop EME/Fullwave FDTD models, respectively.

[4], and shows (see Fig. 2) a set of four modes which span the bandgap ($\mathrm{u} = \mathrm{a/lambda} = 0.23$–$0.31$, where u is normalized frequency, $\mathrm{r} = 1/3\mathrm{a}$, and refractive index $\mathrm{n} = 3.29$). Two of these modes have even symmetry (tripole, $\mathrm{u_A} = 0.244$ and quadropole, $\mathrm{u_D} = 0.295$) with respect to the waveguide (z-axis, Γ-K) and the others have odd symmetry (split quadropole, $\mathrm{u_B} = 0.261, \mathrm{u_C} = 0.267$). The dispersion characteristic of each mode exhibits a characteristic S shape. The group velocity dispersion (GVD), the second derivative of the ω-k plot, was calculated for mode D (plotted in Fig. 3). Significant slowing of the group velocity can be seen at the edge of each of the transmission bands. Choice of mode and operating point allows us access to both regions of positive or negative group velocity dispersion, of the order GVD$\sim\pm1$ ps/nm-mm. In practice, we have only been able to couple significant power through the widest of these even modes (D) and we will concentrate on this mode in the following investigation. It is noted that as these modes all lie above the light line of the $Al_{0.6}Ga_{0.4}As$ buffer, coupling to radiation modes is possible [5].

The results of the bandstructure calculation are valid for an infinitely long, lossless CCW. Our experiments focus upon a very short chain of cavities. In order to model the behavior of the finite length device two models were constructed. Both models include short 2-μm sections of input and output waveguides. The continuous wave (CW) behavior was modeled by a 2-D FDTD beam propagation tool (FullWave—RSoft, Inc.) and by 2-D eigenmode expansion (Fimmprop—Photon Design). The convergence of both models was verified. The transmitted amplitude and phase of the fundamental even modes were recovered. Both models were shown to reproduce the characteristic shape of the transmission band of mode D. The material dispersion of the GaAs/AlGaAs heterostructure waveguide is corrected for in each model. The equivalent index of refraction of the vertical slab mode was solved independently and is used as a 2-D approximation [6]. Experimentally the transmission band is shifted to a higher frequency than that predicted by the 2-D models, this would indicate that the field is concentrated in a medium of lower refractive index than anticipated. We are attempting to determine the nature of this frequency shift; two plausible candidates are either that the material has very slightly oxidised or that the optical mode profile is distributed further into the air and $Al_{0.6}Ga_{0.4}As$ buffer when compared to the slab mode. Understanding this will allow us to feedback into the design process to further correct each model.

An effective index approach then defines a group index $N_g = n - \lambda(dn/d\lambda)$ plotted in Fig. 4, together with the transmitted power. The seven cavities in this CCW should produce seven individual peaks in the transmission spectrum, corresponding to the seven normal modes of the system. We do observe these individual modes, although the first two appear to be merged as indicated by the shoulder on the long wavelength side of the highest frequency peak. The ripple in the group velocity is very pronounced across the transmission peak, due to the short nature of the crystal and high impedance. This should in principle allow pulse compression/dilation at various points across the feature. The GVD for this finite structure is then obtained from, $\mathrm{GVD} = (1/c)(dN_g/d\lambda)$. This is displayed for the crest of the transmission peak in Fig. 5. Peak values of ±10 ps/nm-mm are available and coincide with regimes of high transmission en-

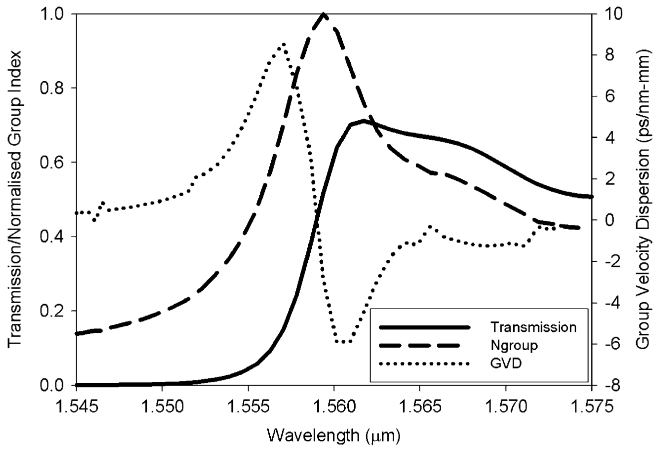

Fig. 5. GVD obtained from Fimmprop data across crest of transmission peak.

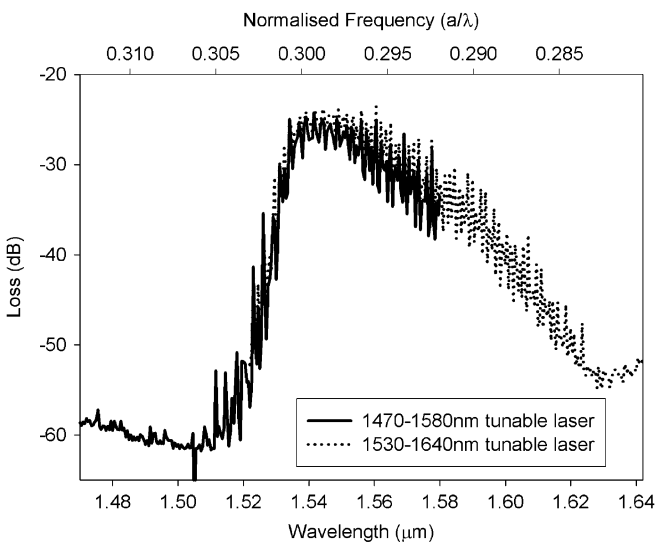

Fig. 6. CW transmission spectrum of mode D for device with lattice constant $a = 460$ nm.

abling experimental verification via pulse propagation measurements.

The TE (**E**|| crystal plane) CW transmission characteristic of the ($a = 460$ nm) device is shown in Fig. 6. A strong rising edge is observed between 1520 and 1540 nm, followed by a slow falling edge. The asymmetry of this band is attributed to the two matching holes that were added to the mask design, in an attempt to impedance match the waveguide. In brief, the transmission band corresponds to the overlapping normal modes of the chain of cavities (with one mode provided per cavity). The distribution of optical power in each normal mode favors the dielectric at the higher frequency band edge and favors the air at the lower frequency band edge. The resonant frequency of the end cavities overlaps the higher frequency band edge, providing efficient coupling to this normal mode and inhibiting coupling at the lower frequency band edge. The result is the characteristic triangular spectrum. The noise apparent on this CW spectrum is due to Fabry-Perot resonances arising from the reflections between the cleaved GaAs facets and the ridge waveguide/PhC interfaces. This can have particularly strong spectral filtering effects on pulses with durations greater than a single round trip

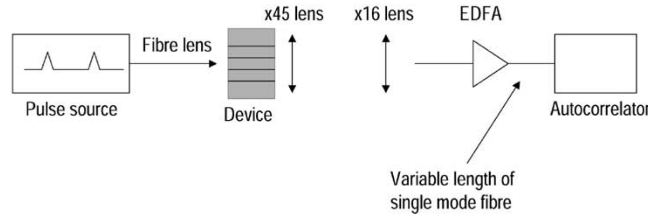

Fig. 7. Experimental configuration for pulse measurements.

of the facet-PhC cavity [7]. In our experiment, this condition is avoided by using 1–mm-long samples and 500 fs pulses. A bandgap does not exist for TM polarization (**E**|| etched holes) with this dielectric configuration, and as such there is no lateral confinement within the CCW, TM polarized light diffracts through the device resulting in very low transmission.

IV. Experiment

Previous measurements of pulses propagating through PhC waveguides have been restricted to spectral or time of flight methods [8]–[12]. Nonlinear analysis of the pulse duration has not been used as a direct measurement of the PhC dispersion. The main difficulties associated with this type of measurement pertain to the obtainable signal level. The dominant loss mechanism is simply the insertion loss into the ridge waveguide. A reflection loss also exists at the ridge/PhC interface due to the impedance mismatch. Propagation loss in these CCWs is not yet fully understood and requires a full 3-D analysis that is currently being conducted. An initial 3-D FDTD estimation points to a loss of the order of 10 dB for this PhC device. The transmission spectra shown in Fig. 6 displays the CW data normalized to the lensed fiber-to-fiber transmission, and indicates a total loss of >20 dB. From comparison with blank ridge waveguides, the PhC is measured to contribute approximately 10 dB of this loss (PhC insertion and propagation loss) the remainder accounted for by the ridge waveguide insertion loss. By operating at the correct wavelength, the availability of two optical amplifiers (EDFAs) allows both the pulsed laser source and the transmitted signal to be amplified, giving a large enough signal for the nonlinear characterization (autocorrelation) of the pulses. The balance of preamplification to postamplification is important in ensuring sufficient gain to overcome losses, while minimizing power within the PhC device to avoid optical nonlinearities. This is further assisted by careful choice of material and laser source to evade these nonlinear processes in the device, which constitute a further possible source of loss [7].

The experimental configuration is shown in Fig. 7. The pulse source comprises a gain switched DFB laser operating at 1536.1 nm with a repetition rate of 1 GHz. The pulses are passed, in turn, through a length of dispersion compensated fiber (DCF) to provide linear pulse compression of the chirped pulse, a length of dispersion shifted fiber (DSF) followed by standard single mode fiber (SMF) to provide nonlinear compression and finally a dispersion-imbalanced loop mirror (DILM) which acts to suppress the pulse pedestal and broaden the pulse spectrum [13]. After compression the pulse is transform limited to a minimum width of 500 fs, as shown in Fig. 8(a), and has a spectral width

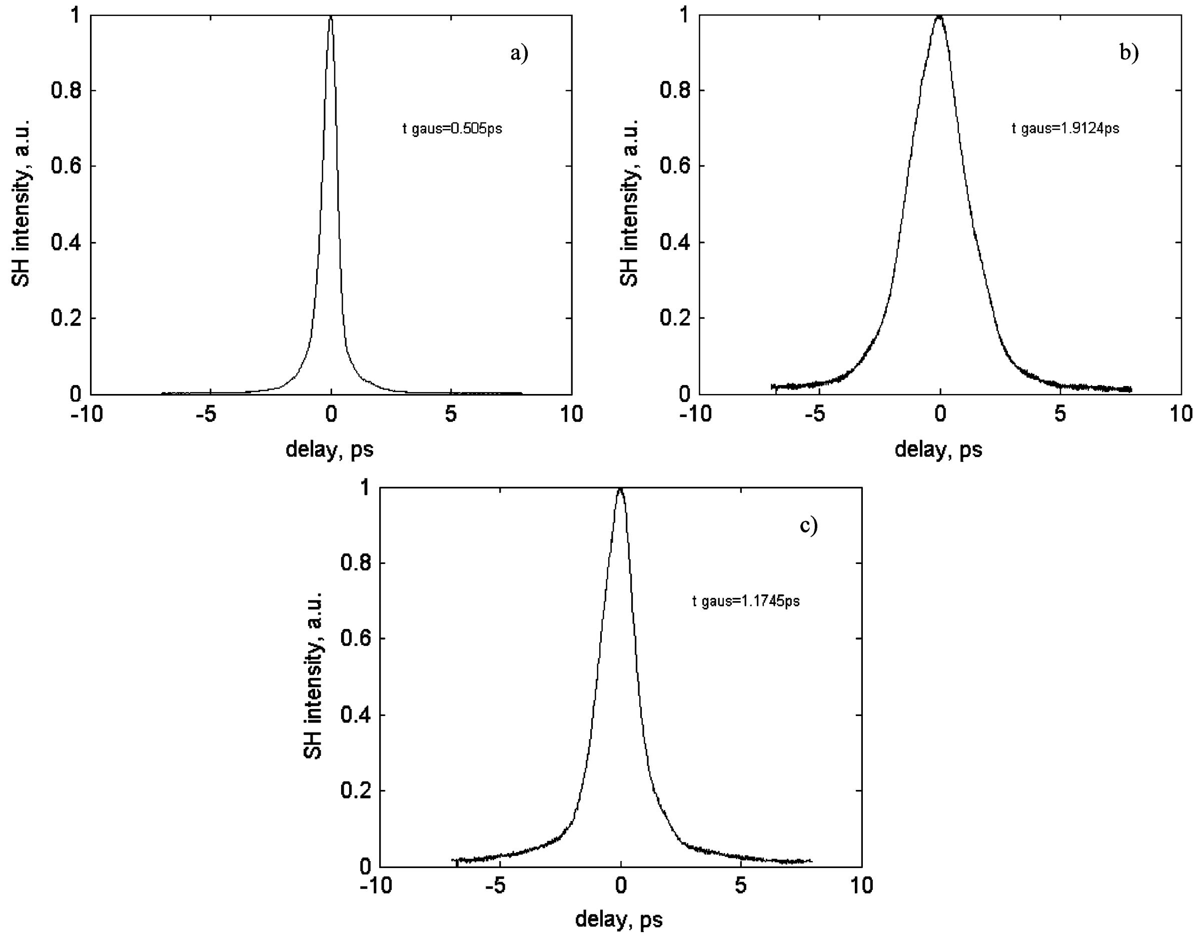

Fig. 8. (a) Autocorrelation of input transform limited pulse observed autocorrelation traces of pulse for same fiber length after transmission; (b) through blank waveguide; (c) through waveguide with L2in1 PhC.

of 7 nm. Due to this short minimum duration, increasing or decreasing the overall length of SMF in the system downstream from the DILM can reliably broaden the pulse. This technique is used to allow pulse compression measurements to be carried out at a range of different input pulsewidths. In order to assess the absolute pulse compression performance of the dispersive PhC, a comparative measurement is made of the pulse transmission through both the PhC and an identical waveguide without a PhC. With the presence of short pulses in such highly confined cavities, one must be wary of nonlinear behavior, and its effect on pulse propagation. An entirely linear behavior was observed at the available power levels [7].

Comparison of autocorrelation measurements of the transmitted pulses is used to determine the dispersion of the PhC waveguide. By adding extra fiber to the system, we can controllably increase the pulsewidth from the initial 500 fs. Examples of the pulses transmitted through a control waveguide [Fig. 8(b)] and the PhC waveguide [Fig. 8(c)] demonstrate the compression effect. We clearly observe that the pulse that passes through the PhC has a significantly shorter duration (1.17 ps) than that passing through the control waveguide (1.91 ps). The PhC CCW, which is only 8 μm long, is therefore responsible for a pulse compression of 40%.

A series of measurements have been carried out to investigate the compression effect of the PhC as the length of SMF

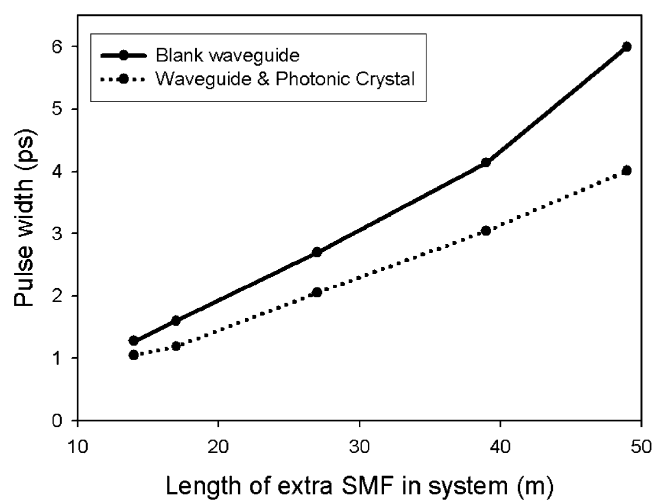

Fig. 9. Variation of pulsewidth with an increase in length of SMF in system.

within the system is greatly increased. Fig. 9 shows the measured pulsewidths for both the control waveguide and the PhC waveguide, indicating pulse duration reductions of up to 2 ps across the range of SMF lengths measured.

Comparisons of the length of fiber in the system required to produce a given pulse duration through the blank waveguide with the pulse durations observed for the PhC waveguide were

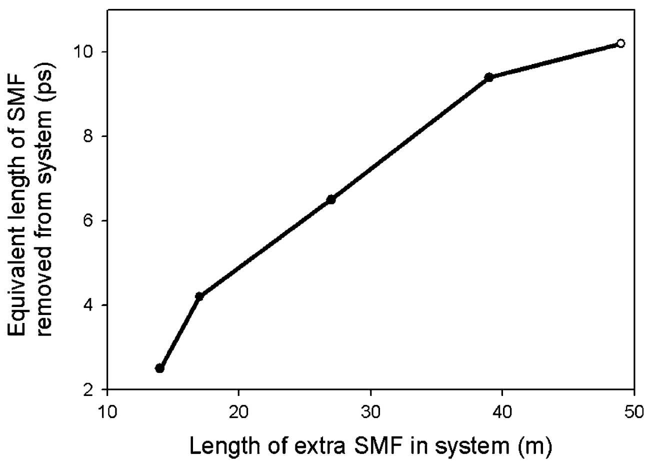

Fig. 10. Equivalent length of SMF required to produce compression observed due to PhC.

then made. These values demonstrate the length of fiber that needs to be removed to produce pulse compression equivalent to that achieved by the PhC. Fig. 10 illustrates these values, showing that the 8-μm-long PhC waveguide can achieve compressions equivalent to SMF lengths of up to 10 m. Thus the dispersion induced by the PhC is $>10^6$ larger than that of standard single mode fiber at these wavelengths.

V. Conclusion

We report the first direct measurement of pulse compression using the large group velocity dispersion available from planar PhC CCWs. Finite length devices have been successfully fabricated in a GaAs/AlGaAs heterostructure and modeled using both 2-D FDTD and 2-D EME. The equivalent dispersion value is $>10^6$ times larger than that available from standard single-mode fiber, in the key telecommunications 1550 nm EDFA window.

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