Wideband slow-light modes for time delay of ultrashort pulses in symmetrical metal-cladding optical waveguide

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Abstract: A widebandwidth optical delay line is a useful device for various fascinating applications, such as optical buffering and processing of ultrafast signal. Here, we experimentally demonstrated effective slow light of sub-picosecond signal over 10 THz frequency range by employing the wide slow light modes in thick symmetrical metal-cladding optical waveguide (SMCOW). Ultrahigh-order guided modes travelling as slow light in waveguide together with strong confinement provided by metal-cladding makes this scheme nearly material dispersion independent and compatible with wide bandwidth operation.

OCIS codes: (999.9999) Slow light; (230.7400) Waveguides, slab; (320.7160) Ultrafast technology.

References and links

1. K. J. Boller, A. Imamolu, and S. E. Harris, "Observation of electromagnetically induced transparency," Phys. Rev. Lett. **66**, 2593–2596 (1991).
2. M. D. Lukin and A. Imamoglu, "Controlling photons using electromagnetically induced transparency," Nature **413**, 273–276 (2001).
3. M. D. Eisaman, A. Andre, F. Massou, M. Fleischhauer, A. S. Zibrov, and M. D. Lukin, "Electromagnetically induced transparency with tunable single-photon pulses," Nature **438**, 837–841 (2005).
4. L. Thevenaz, "Slow and fast light in optical fibres," Nat. Photonics **2**, 474–481 (2008).
5. Y. Okawachi, M. S. Bigelow, J. E. Sharping, Z. Zhu, A. Schweinsberg, D. J. Gauthier, R. W. Boyd, and A. L. Gaeta, "Tunable all-optical delays via brillouin slow light in an optical fiber," Phys. Rev. Lett. **94**, 153902 (2005).
6. Y. A. Vlasov, M. O'Boyle, H. F. Hamann, and S. J. McNab, "Active control of slow light on a chip with photonic crystal waveguides," Nature **438**, 65–69 (2005).
7. T. Baba, T. Kawaaski, H. Sasaki, J. Adachi, and D. Mori, "Large delay-bandwidth product and tuning of slow light pulse in photonic crystal coupled waveguide," Opt. Express **16**, 9245–9253 (2008).
8. T. Baba, "Slow light in photonic crystals," Nat. Photonics **2**, 465–473 (2008).
9. T. F. Krauss, "Slow light in photonic crystal waveguides," J. Phys. D **40**, 2666–2670 (2007).
10. B. Corcoran, C. Monat, M. Pelusi, C. Grillet, T. P. White, L. O'Faolain, T. F. Krauss, B. J. Eggleton, and D. J. Moss, "Optical signal processing on a silicon chip at 640gb/s using slow-light," Opt. Express **18**, 7770–7781 (2010).
11. F. Xia, L. Sekaric, and Y. Vlasov, "Ultracompact optical buffers on a silicon chip," Nat. Photonics **1**, 65–71 (2007).
12. M. O. Fengnian Xia, Lidija Sekaric, and Y. Vlasov, "Coupled resonator optical waveguides based on silicon-on-insulator photonic wires," Appl. Phys. Lett. **89**, 041122 (2006).
13. H. Lu, Z. Cao, H. Li, and Q. Shen, "Study of ultrahigh-order modes in a symmetrical metal-cladding optical waveguide," Appl. Phys. Lett. **85**, 4579 –4581 (2004).

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14. W. Yuan, C. Yin, H. Li, P. Xiao, and Z. Cao, "Wideband slow light assisted by ultrahigh-order modes," J. Opt. Soc. Am. B **28**, 968–971 (2011).
15. H. Li, Z. Cao, H. Lu, and Q. Shen, "Free-space coupling of a light beam into a symmetrical metal-cladding optical waveguide," Appl. Phys. Lett. **83**, 2757 –2759 (2003).

1. Introduction

Slow light, emerging as a technology for optical delays, has many applications for high-performance optical buffering and processing. Over the past decades, slow light generation has been attained in varies media or structures using diverse physical processes, such as atomic vapors with electromagnetically induced transparency (EIT) [1–3], optical fibers with stimulated Brillouin scattering (SBS) [4, 5], photonic crystals (PhCs) [6–10], and coupled-resonator optical waveguide (CROW) [11,12]. Various approaches as there are, the group velocity of optical pulses is reduced exploiting the large dispersion associated with nearby optical resonances. However, the steep dispersion near the resonance of a medium or structure is always too narrow to achieve slow light with broad bandwidth acceptance, which becomes a major limitation of slow light schemes.

Thus, we explore another way to solve this problem by use of wideband slow light based on ultrahigh-order guided modes in a thick symmetrical metal-cladding optical waveguide (SMCOW). Ultrahigh-order guided modes [13], featuring very small propagating constants and anomalous dispersion, are slow propagating modes in optical waveguide which provide a new method in achieving slow light. Moreover, it does not depend on the dispersion caused by material resonance of the guided layer. These advantages combined with strong confinement in visible and near-infrared region by metal cladding make such slow light scheme compatible with wideband operating. Our recent work [14] has demonstrated a delay-bandwidth product (DBP) greater than 2, and this scheme is theocratically predicted to be capable of generating small group velocities over an unusually large frequency bandwidth, which would overcome the limitation of DBP. Here, through ultrahigh-order guided modes assisted slow light we experimentally evaluated a high DBP value of $\sim 10^4$ or $1,400$ fractional pulse delay of a sub-picosecond pulse.

2. Theory

The thick SMCOW has lots of fascinating optical properties over conventional all-dielectric optical waveguide. One unique feature offered by SMCOW is the existing of ultrahigh-order guided modes. (This should be distinguished from Fabry-Pérot based device or folded optical delay lines, where no guided mode is formed.) Usually, the order of existing guided mode in millimeter thick SMCOW can be much higher than 1,000. Thus the polarization depended phase shift in internal total reflection at the dielectric/metal interface is negligible [13]. The waveguide eigen-equation of ultrahigh-order guided modes for both TE and TM polarization is reduced to

$$k_0 h\sqrt{n^2 - n_{eff}^2} = m\pi, \tag{1}$$

where $k_0 = 2\pi/\lambda$ is the wavenumber with the wavelength λ in vacuum, h is the thickness of the guided layer, n is the refractive index of the guided layer, $n_{eff} = \beta/k_0$ is the effective index of the guided mode with the propagation constant β, and m is the mode order. The advantage of SMCOW is that its allowed range of effective index n_{eff} is $n > n_{eff} > 0$, in which the region $1 > n_{eff} > 0$ is totally prohibited in the conventional waveguides [13,15], and this is also the key to understanding the mechanism of slow light in SMCOW. Performing the differential operation of Eq.(1), the group velocity of ultrahigh-order guided modes propagating in SMCOW, defined

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as $v_g = \mathrm{d}\omega/\mathrm{d}\beta$, is then given by

$$v_g = \frac{c}{n_g} = \frac{n_{eff}}{n} \cdot \frac{c}{n + \omega \mathrm{d}n/\mathrm{d}\omega}, \tag{2}$$

where n_g and ω stand for the group index and the angular frequency, respectively.

Unlike most demonstrations of extreme value of v_g in which it relies on the dispersive contribution of medium or structure resonance, the mechanism of ultrahigh-order guided modes assisted slow light relates to their effective index, and is irrelevant to the thickness of SMCOW. Most importantly, the tradeoff between slow-down factor and bandwidth $\Delta\omega$ is avoided. When the actual material dispersion is neglected, the group index of ultrahigh-order guided modes is simplified as $n_g = n^2/n_{eff}$, which is inversely proportional to their effective indices. Slow light is obtained when the effective index n_{eff} approaches zero, in which case ultrahigh-order modes have very small forward components (propagation constant β), i.e., they travel along the waveguide as slow-light modes .

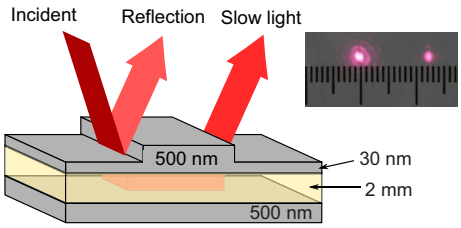

Fig. 1. Illustration of the SMCOW and light coupling method in the experiment. (Inset pic.) The reflected beam (left) and transmitted slow light (right) received on a screen.

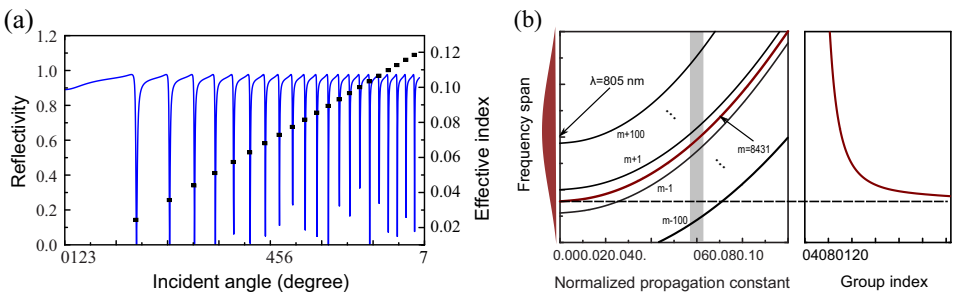

Fig. 2. (a) Simulation of attenuated total reflection (ATR) spectrum and efficient index of the SMCOW using experimental parameters. The wavelength of incident light is set to the central wavelength of the incident light (805 nm). Each dip in the ATR spectrum corresponds to the coupling of light into SMCOW. The black squares is the corresponding effective index of the ultrahigh order mode excited. (b) Schematic diagram of dispersion relation and group-index characteristics for ultrahigh-order modes. Slow light occurs when propagation constant or effective index is small.

When considering ultrashort signals, slow light of such pulses is difficult because of their wide frequency span. Another concerning issue is the serious distortion by the group velocity dispersion (GVD). Significant delay of a signal pulse while preserving its shape requires small group velocity, large spectral bandwidth operation and weak GVD. These competing conditions offset each other. In SMCOW, the ultrahigh-order guided mode is sustainable for arbitrary wavelength, thus slow light effect can be realized over an ultrawide bandwidth, which makes

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slow light of ultrashort pulses in SMCOW possible. The GVD in SMCOW resulting from intramodal dispersion is negative, and can be expressed as

$$\beta_2' = -\frac{n_c^2(n_c^2 - n_{eff}^2)}{\omega_c c n_{eff}^3}, \tag{3}$$

where n_c is the refractive index of the guided layer at the central frequency, and ω_c is the central frequency at a certain mode order. The SMCOW exhibits large anomalous dispersion, typically of the order of $-10^2 \mathrm{ps}^2/\mathrm{mm}$, when n_{eff} is set to 0.06. However, as we will see later, this could be avoided.

3. Experiment and results

To perform a proof-of-principle experiment of the slow light phenomenon of ultrashort pulses based on ultrahigh order guided modes, we have implemented a sample as illustrated in Fig. 1. A two-millimeter-thick glass slab working as the guiding layer is sandwiched between two silver films, which are deposited in vacuum using sputtering method. The upper cladding layer (about 30 nm thick) acts as coupling layer with an additional thick (about 500 nm thick) silver stripe fabricated in the middle of it to prevent light leakage, and the lower thick metal cladding layer is the substrate. The sample functions as three parts: the left and right parts with thin cladding layer are the coupling components, which are used to excite and couple out the ultrahigh-order modes, and the middle part with a length of 12 mm works as an SMCOW. Coupling light into SMCOW and ultrahigh-order guided modes excitement relies on free-space coupling technique [15]. This is possible because the effective index of guided modes in SMCOW can be smaller than that in air. Figure 2(a) shows the simulation of attenuated total reflection (ATR) spectrum of the SMCOW at the incident central frequency, which defines the coupling angle. The favorite characteristic of thick SMCOW is that it still satisfies coupling condition at near-normal incidence. However, due to the wide frequency span the signal light coupling is significantly weakened, because the phase-matching condition is different away from central frequency. The dispersion relation and group-index characteristics for ultrahigh-order modes in thick SMCOW are schematically depicted in Fig.2(b). The group velocity is derivative of frequency with respect of propagation constant or the slop of the dispersion curve, which decreases as propagation constant gets smaller.

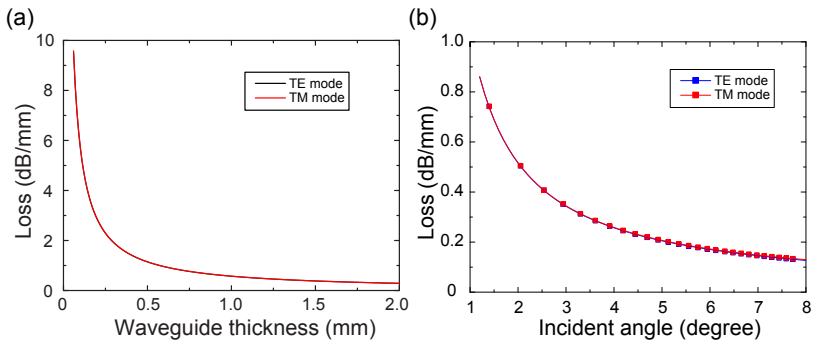

Fig. 3. (a) The loss versus waveguide thickness at the incident angle of 3.6°. The propagation loss is moderate small for sub-mm or mm scale SMCOW. (b) The loss versus incident angle at the thickness of 2 mm. The loss is nearly the same for both TE and TM ultrahigh-order modes.

The reason for the use of millimeter scale SMCOW is twofold: First, there is no ultra-high order guided modes near small effective index condition in micro-meter SMCOW, that is, no

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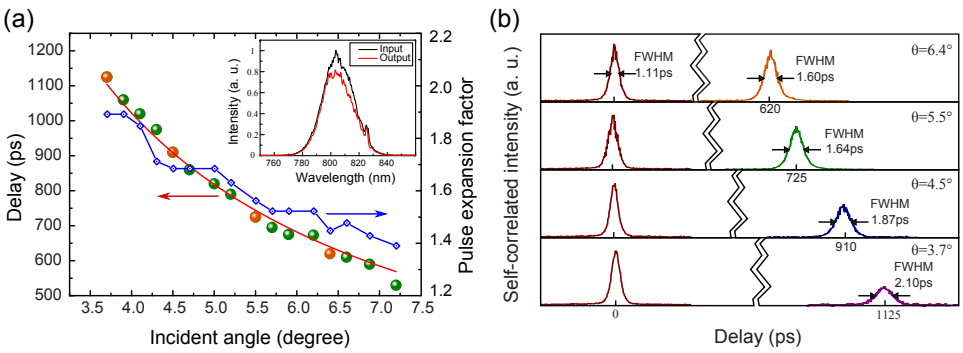

Fig. 4. (a) Measured absolute time delay and pulse expansion at different coupling angles. Self-correlation width of the incident pulse is 1.11ps (785 fs for Gaussian, or 720 fs for Sech^2 pulse profile). The solid curve is the theoretical fitting. (Inset) A typical input and output spectra. (b) Self-correlation trace of the optical pulse at each time delay denoted by the yellow filled circles plotted in (a).

slow light effect. The second is about the loss due to the absorption of cladding metal. Everyone has, perhaps conveniently, been in the position of believing light could not propagate in the length scale of mm in metal-cladding waveguides due to 'strong' metal absorption in optical frequency. In fact, the loss could be greatly reduced by extending the thickness of guided layer to sub-mm or mm scale. The intrinsic loss of metal cladding relates to the imaginary part of metal susceptibility. This could be represented by the imaginary part of propagation constant β, which could be precisely deduced from first-order perturbation theory. Figure 3(a) shows the calculated loss of SMCOW due to metal absorption at a small coupling angle. The propagation loss is actually rather low and degenerate, which proves validation of long propagation length of ultrahigh-order guided modes.

In our experiment, femtosecond pulses centered at 805 nm generated from a Ti:Sapphire laser system are used, which have a frequency span over 10 THz (FWHM). The signal is stretched to sub 1 picosecond (self-correlation FWHM 1.11 ps) by introducing positive chirp to prevent optical damage to the thin coupling layer, then directly coupled into SMCOW by use of free-space coupling technique. The signal is coupled into the waveguide at a set of discrete small incidence angles ($3.7^\circ - 7.2^\circ$ in our experiment) when verifying the coupling condition as shown by the ATR spectrum. The mode density of ultrahigh-order modes in the limit of near normal incidence is sparse, thus a pure ultrahigh-order mode could be excited for each frequency component of the signal within the beam divergence. The corresponding effective indices at central frequency is also plotted in Fig. 2(b). The reflected beam branch is used as a reference for time delay measurement (cross correlation method). The other branch, after propagating through the SMCOW, is coupled out from the right part of the sample with temporal shifts. A photograph of the reflected and transmitted light on a screen is shown in the inset of Fig. 1(a). In this scheme, according to phase matching condition, the effective index of guided mode is given by $n_{eff} = n_0 \sin\theta$, where n_0 is the refraction index of air, and θ is the incident angle. The effective index n_{eff} can be tuned toward zero just by decreasing the incident angle. Therefore, under small angle incident condition, the group velocity of the guided modes is dramatically reduced, opening a new approach to achieve slow light.

The experimental measured time delay at different incident angles is illustrated in Fig. 4, which agrees with theoretical prediction. The absolute time delay of the transmitted slow light was measured by a method similar with cross-correlation with an accuracy of 15 ps. We spatially delayed the reflected pulse using a variable delay line, and overlapped it with the trans-

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mitted slow light in a nonlinear crystal (BBO). Therefore, the delay time induced by SMCOW is equivalent to that delayed by the delay line. The experimental obtained large time delay and pulse expansion factor is plotted in Fig. 4(a). Data at smaller incident angle was not measured due to practical constraints. Typical spectra of the input and output are shown in the inset, which proves the capability of wideband operating. Tuning of pulse time delay is achieved by changing the incident angle. The maximum absolute time delay obtained is 1,125 ps at the incident angle of 3.7 degree, with pulse expansion factor of 1.9. This corresponds to fractional pulse delay exceeding 1,400, or DBP value of 10^4. In principle, this can still be further increased. Figure 4(b) shows several measured self-correlated traces of the input and output pulses at difference conditions, which indicates no severe pulse expansion. Although the total loss is practically measured to be approximate one order of magnitude larger than propagation loss theoretically predicted, the result is still quite astonishing when taking into account coupling inefficiency, imperfect metal cladding and light scattering.

In general, the GVD in SMCOW results from material, intramodal and intermodal dispersion. Since the slow light is achieved far away from the material resonance, the material dispersion could be minimized. When considering the pulse expansion, the intermodal dispersion can be negligible, because the signal is distributed among a series orders of propagating modes with the same effective indices; this is shown by the gray zone in Fig. 2(b). The dominant dispersion in SMCOW is the strong intramodal dispersion. However, the frequency component distributed to a certain ultrahigh-order mode, given by

$$\Delta\omega = \pi\frac{c}{h}(n^2 - n_{eff}^2)^{-1/2}, \tag{4}$$

is only around 50 GHz. This explains the weak expansion of the signal under strong GVD. By distributing wide spectrum among a large number of different modes, the actual pulse expansion is moderate small even under strong mode dispersion condition.

It's also worth mentioning that the experimental results are polarization insensitive, which agrees with theoretical modelling. Although light slowness is only achieved at discrete conditions at small incident angles, it can be continually tuned by substituting the guide layer with electro-optical material with external electrical signal modulation, since the group velocity of light in SMCOW is also sensitive to the change of material index (see Eq. (2)). Overall, this scheme possesses excellent slow light performance, is achievable over a large bandwidth, and only introduces small distortion to the ultrashort pulses, thereby allows for exciting promises in the field of ultrafast optical buffering or processing.

4. Conclusion

In conclusion, ultrahigh-order guided mode could be considered as a new kind of slow-light mode. In experiment, we have demonstrated a novel ultrahigh-order guided modes assisted slow light scheme in SMCOW with widebandwidth operation for time delay of sub-picosecond pulses. The main advance is based on the small effective index of ultrahigh-order guided modes, which is a linear physical process. We believe slow light in SMCOW featuring room-temperature operating, large fractional pulse delay and small footprint would be of practical importance in applications of ultrafast optics, optical buffering, etc.

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