A Compact and Transmissive Device for Dispersion-Compensation of Ultra-short Optical Pulses

Yong LEE

Central Research Laboratory, Hitachi Ltd., 1-280, Higashi-koigakubo, Kokubunji, Tokyo, 185 Japan

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We show by computer simulation that a coupled-cavity-type multilayered structure is suitable for the transmissive compensation of group-velocity dispersion for optical pulses of subpicosecond length, and can thus be used to make a simple, compact, and transmissive dispersion-compensation device.

Key words: group-velocity dispersion, dispersion-compensation, pulse compression, pulse recompression, chirped optical in-fiber Bragg gratings, split-step modified beam propagation method

1. Introduction

Dispersion compensation is of great importance for pulse compression and recompression in ultrashort-pulse laser systems as well as in high-bit-rate optical communication and soliton transmission systems. The conventional dispersion-compensation elements—dispersive optical fiber,1) grating pairs,2) and Gires-Tournois interferometer3)—are bulky and are thus not suitable for use in actual laser and communication systems. Several compact dispersion-compensation devices have recently been proposed,4-8) and some of them have been demonstrated experimentally.7-9) The proposed devices are of two kinds, and the operation of one kind is based on the coupling of two waveguide modes that have different group velocities, leading to a large dispersion. This coupling can be achieved by using a dispersive filter with a chirped periodic refractive-index perturbation10) or a waveguide structure consisting of two dissimilar waveguides.8) Devices of this kind are transmissive, and this property makes their alignment and integration in laser and optical communication systems feasible.

The other kind of dispersion-compensation devices makes use of a relatively large dispersion in the Bragg stop-band gap, induced by multiple reflection in multilayered structures, such as chirped Bragg-grating dielectric mirrors9) and chirped optical in-fiber Bragg gratings.5,6) The advantage of these devices over the former ones is that a coupling efficiency of an input pulse with the device is high due to layered structures. Devices of this kind, however, are reflective and therefore hard to align and integrate in laser and optical communication systems.

In devices of this kind, a large dispersion can be obtained in the transparent region next to the Bragg stop-band gap. However, the spectral bandwidth of the transparent region is much narrower than that of subpicosecond pulses. In this letter, we show that a coupled-cavity-type multilayered structure is suitable for a simple, compact, and transmissive dispersion-compensation device for subpicosecond pulses. A device with this structure uses a nearly perfectly transparent region next to the stop-band gap. The magnitude of the dispersion in that region is sufficiently large for subpicosecond pulses, and the spectral bandwidth of the transparent region is also large enough to cover that of subpicosecond pulses. Note that the term "subpicosecond" used throughout this letter means a time scale of the order of 100 fs.

2. Numerical Examples

As shown in Fig. 1(a), the coupled-cavity-type multilayered structure (CCMLS) we evaluated numerically consists of two half-wavelength (λ/2) cavity regions sandwiched by standard quarter-wave dielectric mirrors (QWDMs). Assuming that semiconductor materials are used, we chose the reflective indices of the low-index and high-index materials and the outside material to be 3.0, 3.6, and 3.2. The reflection spectrum of this structure, shown in Fig. 1(b), was calculated using a well-known transfer matrix method.10) For comparison, the reflection spectrum of a standard QWDM having the same number of layers and the same reflective indices as the CCMLS is also shown in Fig. 1(b). A clear difference between the two structures is the size of the spectral bandwidths of the transparent regions next to the stop-band gaps: the bandwidth of the CCMLS in the region of λ =1480 nm-1570 nm is about 20 times that of the QWDM around λ =1490 nm. Analysis of the electric field distributions inside the structure revealed that the wider bandwidth for the CCMLS is associated with the excitation of higher-order modes that have wider bandwidths. The group-velocity dispersion (GVD) in the transparent region calculated for the CCMLS is shown in Fig. 1(c). The GVD is kept nearly constant at about −1×10−26 s4, under extremely low reflectivities, over a bandwidth of roughly 30 nm, which is almost equal to the bandwidth of 100-fs pulses with a central wavelength of 1.5 μm. This result indicates that the CCMLS is potentially very useful as a transmissive dispersion-compensation device for subpicosecond pulses. We do not discuss a third-order dispersion effect because the third-order dispersion does not play an important role in the distortion of subpicosecond pulses (>100 fs) considered here, and it becomes important for pulses less than the order of 10 fs. The positive sign of GVD, for instance, can be obtained in the transparent region on the opposite side of the stop-band gap.
Although the values plotted in Fig. 1 were calculated for a CCMLS with two cavities, a CCMLS with more than 3 cavities is expected to have a wider spectral bandwidth of the transparent region next to the stop-band gap. The value of GVD decreases, however, with increases in the number of cavities, so there is a trade-off between the bandwidth and GVD.

We also performed a computer simulation to evaluate the propagation of an up-frequency-chirped ultrashort pulse. The CCMLS in this simulation is the same as the one just described except that, because the range of the choice of the parameters is limited by the capability of the computer used, (i.e., the CPU time and the capacity of memories) to obtain numerically reliable results, we set $n_L=1.0$, $n_i=1.2$, and $n_s=1.0$ which are different from the indices used in the calculations shown in Fig. 1(b) and (c). Since the calculation of the propagation is a linear calculation, we can expect to obtain the same result as that of the present case ($n_L=1.0$, $n_i=1.2$, and $n_s=1.0$) in other sets of indices such as semiconductor materials. The central wavelength $\lambda_0$, the full width at half maximum (FWHM), the peak power and the cross-sectional area of an incident chirped pulse with a Gaussian profile were chosen to be 1.5 \(\mu\)m, 125 fs, 1W and 100 \(\mu\)m². The chirped pulse was generated by letting a transform limited pulse go through a region with Kerr-type nonlinearity. The third-order nonlinear coefficient and the length of the nonlinear region were $\chi^{(3)}=7\times10^{-14}$ (m/V)² and 5 $\lambda_0/n_0$. The numerical method used was the split-step modified beam propagation method in the time domain—recently developed by Scalora and Crenshaw, where Maxwell's equation for the propagation of electromagnetic waves is solved by making use of the slowly varying envelope approximation in time only (SVEAT). This method is particularly useful for our example because it can handle reflections without requiring the introduction of explicit boundary conditions. The calculated dynamical behavior of the propagation of the chirped ultrashort pulse in the CCMLS is shown in Fig. 2, where intensity is plotted against the scaled length coordinates, $\xi=z/\lambda_0$. The chirped pulse traveling from the left-hand side of the CCMLS is, as expected, compressed by a factor of about 2 in transmission. The transmission coefficient, $\approx 95\%$, is high enough for the CCMLS to be used as a transmissive dispersion-compensation device. The compressed pulse is somewhat distorted, and there are two reasons for this distortion. One is that the positive GVD of the CCMLS is not perfectly constant over the spectral bandwidth of the incident chirped pulse, and the other is that the effect of the third-order dispersion might be present.

3. Summary

Our computer simulations have shown that a coupled-