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1.B Shaping and Measuring a Laser Pulse Using Spectral Beam Deflection

The capability to produce laser pulses of arbitrary temporal shape is important in areas of optical communication,[1] atomic and molecular spectroscopy,[2] and laser fusion.[3] Previous pulse-shaping techniques have achieved moderate success in these areas.[4–6] The new approach discussed here, using the technique of spectral beam deflection (SBD), offers the potential of higher temporal resolution combined with the flexibility of beam-size variation and aperture-position variation during the pulse. SBD can produce the high-precision multinanosecond pulses required for laser fusion applications, and it is compatible with standard pulse-compression techniques for producing shaped subpicosecond pulses. Although SBD is applied here mainly to pulse shaping and beam-size shaping, it is a general technique that can be used for any application that requires laser-beam scanning for illuminating an object or for reading and writing information.

Laser-beam temporal pulse shaping has previously been performed in both the time domain[4,5] and frequency domain.[6] Time-domain shaping [Fig. 50.11(a)] is accomplished by passing the beam through, for instance, a Pockels cell placed between two polarizers that will cause time-dependent attenuation of the beam when driven by a shaped electrical pulse. This approach relies on electronic techniques for constructing the required temporal electrical shape. At present, it has been difficult to produce very complicated or very fast rising pulses. The second approach, pulse shaping in the frequency domain [(Fig. 50.11(b)], is accomplished by spatially separating the spectral components of the beam (using a diffraction grating) and modifying the amplitude and/or phase of these components to produce the spectrum that corresponds to the desired temporal pulse shape. When the spectral components are recombined, very complicated

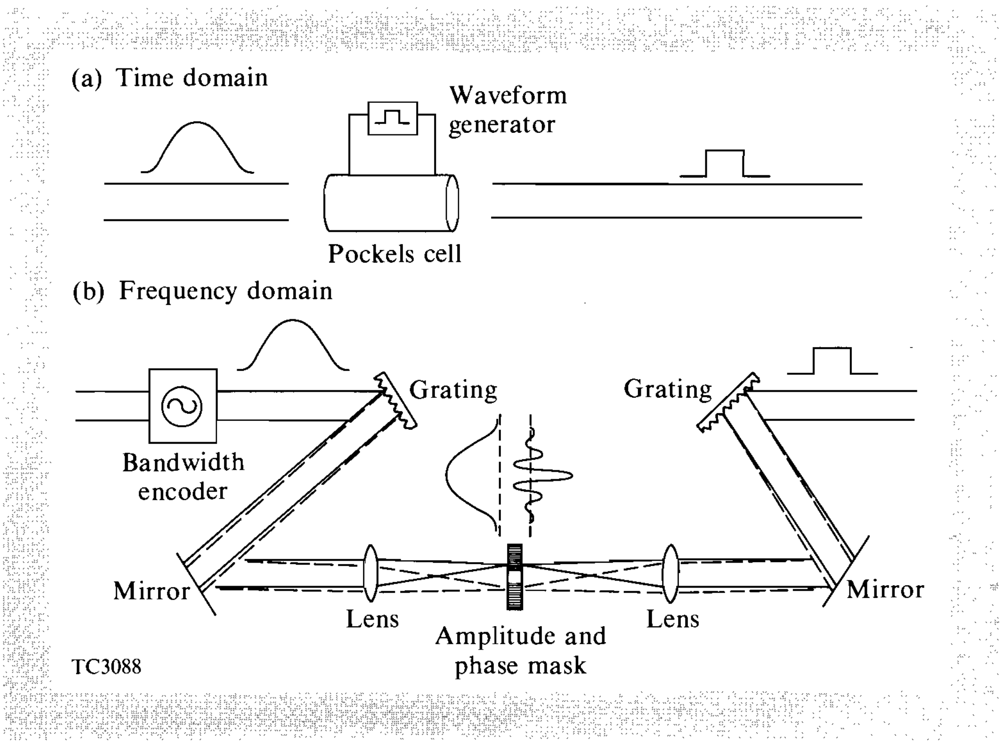

Fig. 50.11
There are two generic techniques for laser-beam pulse shaping: (a) time-domain shaping uses a temporally shaped electrical current to produce a time-varying attenuation of the beam; (b) frequency-domain shaping separates the pulse into its spectral components, and then modifies the relative amplitudes and phases of these components to produce the spectral distribution of the desired pulse shape.

pulse shapes can, in principle, be produced. However, in order for the spectral components to combine properly, generally both the amplitudes and phases must be fashioned to an extremely high level of precision, since each spectral component will affect the pulse throughout its entire temporal duration. Such precision has been difficult to obtain, and as a result, this technique has been applied only to relatively simple pulse shapes.

The pulse-shaping technique discussed here is a hybrid between the time-domain and frequency-domain approaches, and it uses the best features of each. It has the advantage of the time-domain approach in that each temporal region of the pulse is constructed relatively independently of the other regions. However, unlike time-domain shaping the pulse is not constructed using time-varying electrical pulses but rather using static filters, which is one of the attractive features of frequency-domain shaping. This hybrid approach is accomplished by passing the beam through a device that causes temporal deflection of the light (Fig. 50.12). When the beam is focused by a lens, the position of the focal point will change in time as the beam is deflected, creating a one-to-one mapping between time during the pulse and spatial position in the focal plane. Intensity attenuation in a spatial region in the focal plane will then produce attenuation in the corresponding temporal region of the pulse when the beam is returned to its far-field position.

Pulse shaping by beam deflection has been previously examined using electro-optic prisms to produce the deflection.[7] Here we use SBD to produce the beam deflection. This results in greater flexibility and potentially higher resolution. For example, SBD is sufficiently flexible that it can directly accommodate the option of pulse compression to produce shaped subpicosecond pulses. Also, with

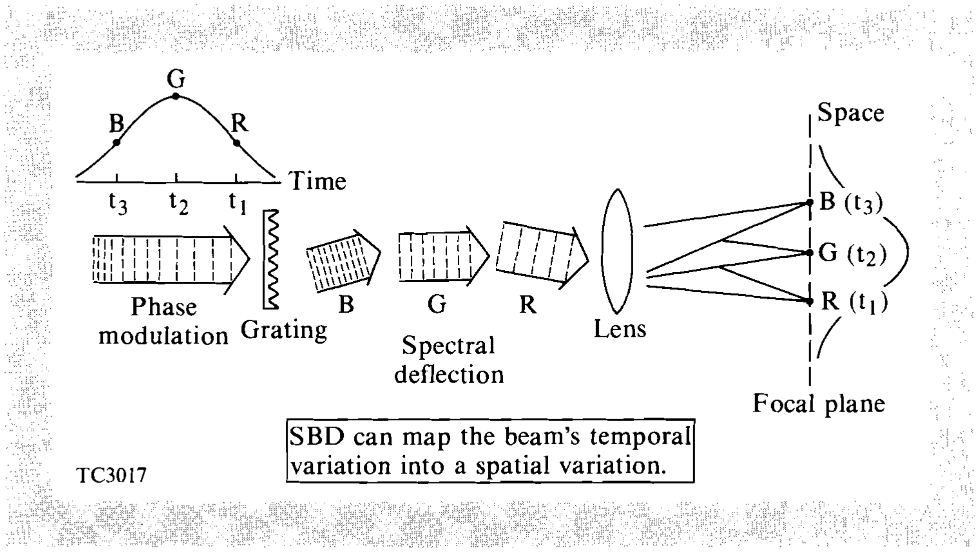

Fig. 50.12
Spectral beam deflection (SBD) maps a beam's temporal variation into a spatial variation by means of whole-beam deflection. The deflection is produced by coarse dispersion of a frequency chirp that was imposed upon the beam.

a small extension of the pulse-shaping configuration, SBD will allow temporal changes of the beam size as well as changes of the beam location within the aperture (including the production of multiple beams within the same aperture). Finally, the time-to-space mapping produced by beam deflection has been proposed for constructing an optical streak camera to measure the temporal pulse shape of a laser beam.[8,9] A more general configuration, based on SBD, is discussed here.

Description of Spectral Beam Deflection

The method for achieving beam deflection with the SBD pulse-shaping technique is illustrated in Fig. 50.12. Starting with a generic pulse, the first step is to impose phase-modulated bandwidth upon the beam such that the instantaneous frequency (time derivative of the phase) is changing monotonically throughout the pulse. This assigns to each point in time during the pulse a unique characteristic spectral frequency. The required modulation bandwidth is typically 10–100 times the Fourier-limited bandwidth of the desired pulse shape. (The higher the bandwidth, the greater the possible temporal resolution). Two methods of bandwidth generation are currently under investigation. One approach is to pass the beam through an electro-optic (E-O) modulator driven by microwaves. The modulation frequency and phase are chosen so that a half cycle, containing the extremes of the bandwidth, encompasses the pulse, with the central frequency at (or near) the peak of the pulse. After the pulse shaping, excess bandwidth can in principle be removed by passing the beam through a modulator a second time, but 180° out of phase. The second approach being considered for bandwidth generation is to chirp the pulse by passing it through an optical fiber. This approach has been used extensively for pulse compression to generate subpicosecond laser pulses. It has the advantage of centering the frequency chirp around the peak of the pulse without requiring the synchronization needed for an E-O modulator. The disadvantage is that the bandwidth cannot be removed (except by using a properly synchronized E-O modulator), and also the early and late parts of the pulse might not be properly chirped and could require some truncation.

Deflection of the beam is now achieved using a diffraction grating. Each point in the pulse will be deflected in a direction determined by a small spectral range around the instantaneous frequency of the phase-modulated bandwidth. When the beam is focused, the deflection will cause each region of the pulse to be mapped into a unique region in the focal plane (Fig. 50.12). (This technique was applied in Ref. 9 for application to an optical streak camera.) There will be some spatial overlap of neighboring temporal regions because of the finite spot size of the beam, the beam's intrinsic bandwidth, and because of spectral components that are common to both temporal regions. The amount of overlap determines the resolution of this technique.

Spectral separation of the bandwidth in the focal plane of a lens is very suggestive of the frequency-domain pulse-shaping approach [Fig. 50.11(b)]. However, there is one important difference. Frequency-domain shaping requires high spectral resolution, and it has been applied to situations where the pulse is bandwidth limited (i.e., the spectrum is dominated by the amplitude variation of the beam). In that situation there is no direct relationship between a frequency interval and a temporal range in the pulse, and both the phase and amplitude must be shaped very precisely in order for the spectral components to recombine into the required pulse shape. (Specifically, it is the Fourier transform of the pulse that must be shaped.) For SBD, the bandwidth is chosen sufficiently large that the spectrum is dominated by the phase modulation, and an "instantaneous" frequency relating time and space is well determined. In the focal plane there is a sufficiently large spectral overlap that a close correspondence between time and instantaneous frequency can be maintained. The result of the spectral dispersion with SBD is predominantly whole-beam deflection. Because of the direct space-time mapping, the pulse shape itself is constructed and not its Fourier transform. Only amplitude attenuation, and not phase modification, is required. The E-O modulator and grating combination used for SBD is similar to the configuration used for the beam-smoothing technique known as smoothing by spectral dispersion (SSD).[10] Indeed, in some SSD configurations, whole-beam deflection has been observed.

An alternate method for producing temporal beam deflection is to use an electro-optic prism.[7] The advantage of the technique proposed here is that the phase-modulated bandwidth and the beam deflection are produced by two separate components. This results in considerably more flexibility, and it allows each component to be separately optimized to maximize its effect. With the E-O prism, beam deflection must be imposed electro-optically, and it can only be removed by passing the beam a second time through a properly synchronized E-O prism. With SBD, pulse shaping can be performed using totally passive optical components for those applications that do not require removal of the bandwidth, thus avoiding the complications of synchronization with the pulse. The bandwidth can be imposed with an optical fiber, and the deflection is imposed and removed with diffraction gratings. For applications that do require bandwidth removal or if there are advantages for imposing the bandwidth electro-optically rather than with a fiber, then SBD will require the same level of synchronization as the E-O prism. However, there are still advantages to separating the E-O component from the deflection component as done in SBD.

First, the diffraction gratings used with SBD can generate considerably more angular dispersion than prisms, producing a greater amount of deflection in the focal plane of a lens. Second, multiple-pass configurations can be optimized for each component separately for increasing either the bandwidth or the dispersion or both. Third, the beam size can be chosen optimally for each component: it is easiest to impose E-O modulation on a small beam whereas high spectral resolution is obtained with a large beam. Finally, the same bandwidth that is imposed for SBD can also be used for additional modifications of the beam, such as changing the beam size during the pulse, as discussed in the next section.

Applications of SBD

We consider four applications of spectral beam deflection: (1) pulse shaping; (2) combining pulse shaping with pulse stretching (and compression); (3) changing the beam size and shape during the pulse; and (4) measuring the beam intensity as a function of time (optical streak camera).

1. Pulse Shaping

Pulse shaping is accomplished by placing attenuation filters in the focal plane where the beam's temporal variation has been mapped into a spatial variation (Fig. 50.13). The spatial variation of the attenuation is the same as the desired temporal shape, except for a scale adjustment to account for any nonlinearity in the space-time mapping. (For sinusoidal E-O modulation, the space variable x in the focal plane and time variable t are related by $x \sim \sin \omega_m t$, where $\omega_m/2\pi$ is the oscillation frequency of the modulator. Since the modulation frequency is chosen such that there is less than 1/2 of a cycle across the pulse, with the center frequency at the center of the pulse, this mapping is single valued.) The amplitude attenuation can be performed by separate filters for each individual pulse shape, or by a general two-dimensional addressable array of liquid-crystal polarizer elements that can be modified electronically. Modulators made from liquid-crystal display cells have been used for phase modification.[11] They can also be used for amplitude attenuation by inducing a polarization rotation followed by a polarizing analyzer.

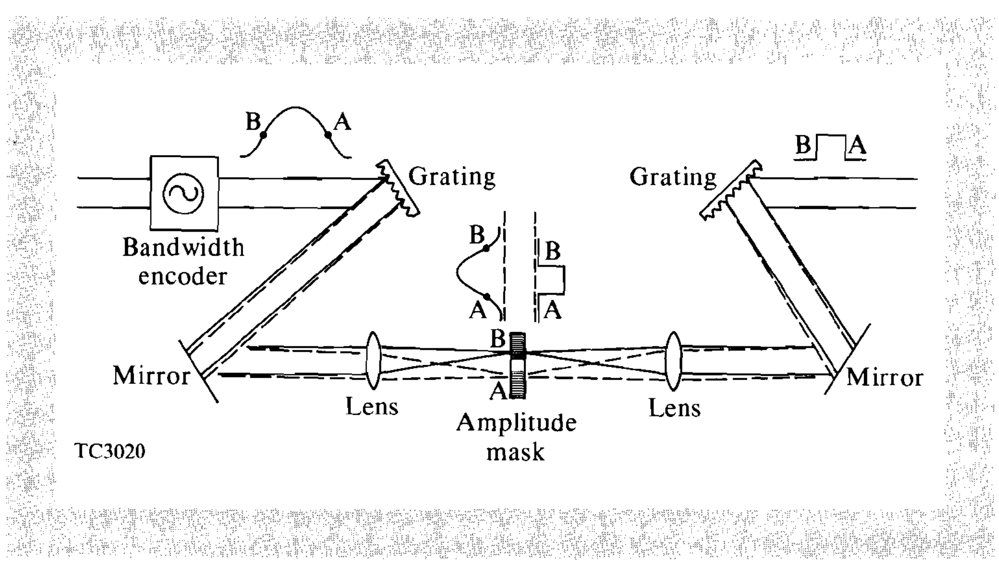

Fig. 50.13
SBD pulse shaping is a hybrid between time-domain and frequency-domain shaping. Spatial amplitude attenuation follows the temporal shape of the beam. (Phase modification is not required.)

After the spectral encoding and filtration, the beam is recollimated with a lens and the spectral dispersion is removed with a second grating. At this point, temporal pulse shaping has been achieved. In general, only a small fraction of the encoded bandwidth has been used to shape the pulse, and the remainder is still in the form of phase modulation. The following options are available for continued manipulation of the beam:

(a) If the excess bandwidth remaining on the beam is too large (as can happen for a frequency-tripled laser that has a narrow bandwidth acceptance for high-efficiency frequency conversion), then a majority of the bandwidth can be removed by passing the beam through an E-O modulator a second time operating at the same frequency and modulation index but 180° out of phase.

(b) The bandwidth can be used for other applications such as beam-size shaping.

2. Combining Pulse Shaping with Pulse Stretching

Pulse shaping by SBD can be further enhanced by combining it with the option of pulse stretching or compressing. This is illustrated schematically in Fig. 50.14. The double-grating technique of changing the pulse width for a chirped pulse has been used extensively in picosecond experiments,[12,13] but it can be used for multi-nanosecond pulses. This technique can be useful when a variety of different pulse widths are required, and it is not convenient to constantly modify the laser oscillator to generate the different pulses. In this case, the oscillator would produce a Gaussian pulse with always the same width. The pulse would be chirped with the quasi-linear portion of sinusoidal E-O modulation; the direction of the chirp will be chosen according to whether the pulse is to be compressed or stretched.

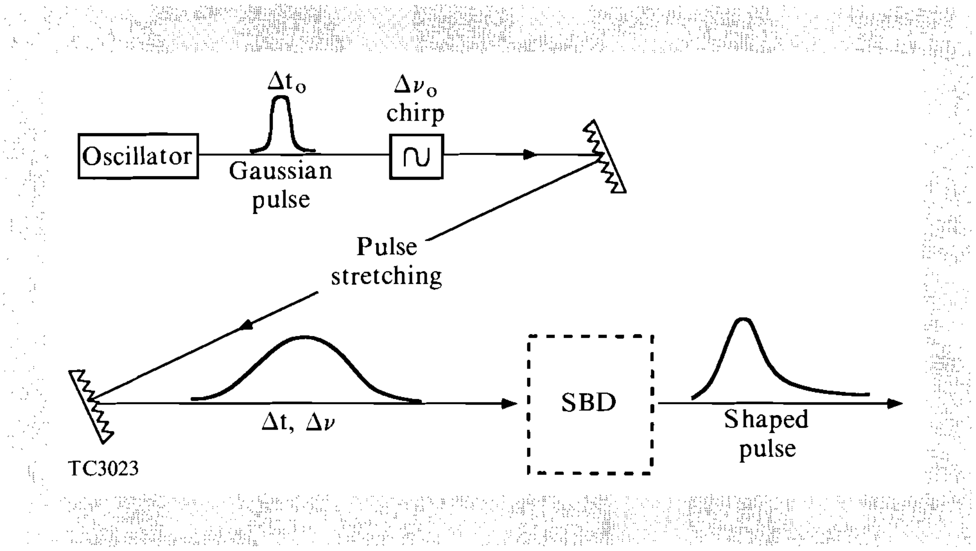

Fig. 50.14
A two-grating configuration can be used to stretch (or compress) the beam prior to SBD shaping.

By passing the beam through the double-grating configuration, the pulse can, in principle, be stretched from say 100 ps to several nanoseconds or compressed to picoseconds. For multi-nanosecond stretching, it may be necessary to pass through the gratings several times to achieve the required time delay. The number of passes is determined by the bandwidth, the grating dispersion, and the distance between gratings. After a large number of passes, it might be necessary to amplify the beam to compensate for grating losses. With a linear chirp, the pulse will maintain a Gaussian temporal profile.

For a proper adjustment of the distance between the gratings, the resulting pulse will remain linearly chirped, though the direction of the chirp can be reversed. This same chirp can now be used with SBD to shape the pulse. No additional bandwidth is required.

Pulse shaping within the double-grating configuration has been previously examined.[14,15,16] In general, it will provide less temporal resolution than shaping separately by SBD.

3. Beam-Size Shaping

The beam size, shape, and position within the aperture can be changed as a function of time by a small variation of the previously mentioned pulse-shaping technique. Instead of using circular lenses to focus the beam, cylindrical lenses are used as illustrated in Fig. 50.15. This allows access in the focal plane to one spatial dimension of the beam as a function of time. By using attenuation filters this dimension can be shaped in time. Returning to the near field the beam is recollimated and the spectral dispersion is removed by a grating. To modify the second dimension of the beam, the beam is passed through a grating oriented to disperse the beam in the perpendicular direction, and the process is repeated. Note that all this manipulation uses the same phase-modulated bandwidth; the bandwidth has to be encoded only once.

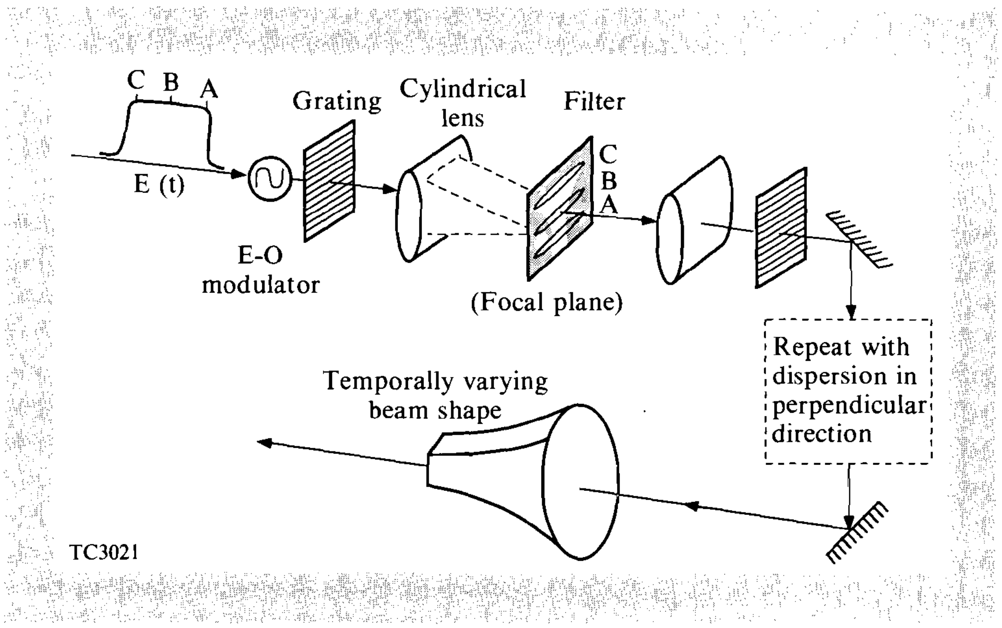

Fig. 50.15
The beam size and shape can be varied during the pulse by using cylindrical lenses to focus the beam. This gives access to one dimension of the beam for modification as a function of time.

4. Optical Streak Camera

The time history of the pulse can be measured by placing a photosensitive device such as film in the focal plane where the beam has been deflected and is spatially displayed. If no other bandwidth has been placed on the beam besides that used for beam deflection and if the intrinsic bandwidth of the pulse is small, then the measuring device can simply be placed in the focal plane of the configuration in Fig. 50.12 (see also Ref. 9). However, if the beam is to be measured after additional bandwidth has been placed on it, such as bandwidth used for beam smoothing, then in general there would no longer be a one-to-one relationship between time during the pulse and spatial position in the focal plane. To accommodate this situation, the configuration in Fig. 50.16 could be used.

The configuration of gratings and E-O modulators shown in Fig. 50.16 accomplishes two goals: (1) any bandwidth on the beam prior to the first grating in the figure will not contribute to the beam deflection and (2) the modulators are not required to be synchronized with the peak of the pulse. It is straightforward to show that the gratings have no effect on any bandwidth that was not imposed by the two modulators. For pre-existing bandwidth the first grating will disperse the bandwidth in the x direction; the second grating will remove that dispersion. Similarly, the third grating will disperse the beam in the y direction, but the fourth grating will remove the dispersion. Only bandwidth imposed by the modulators will be dispersed.

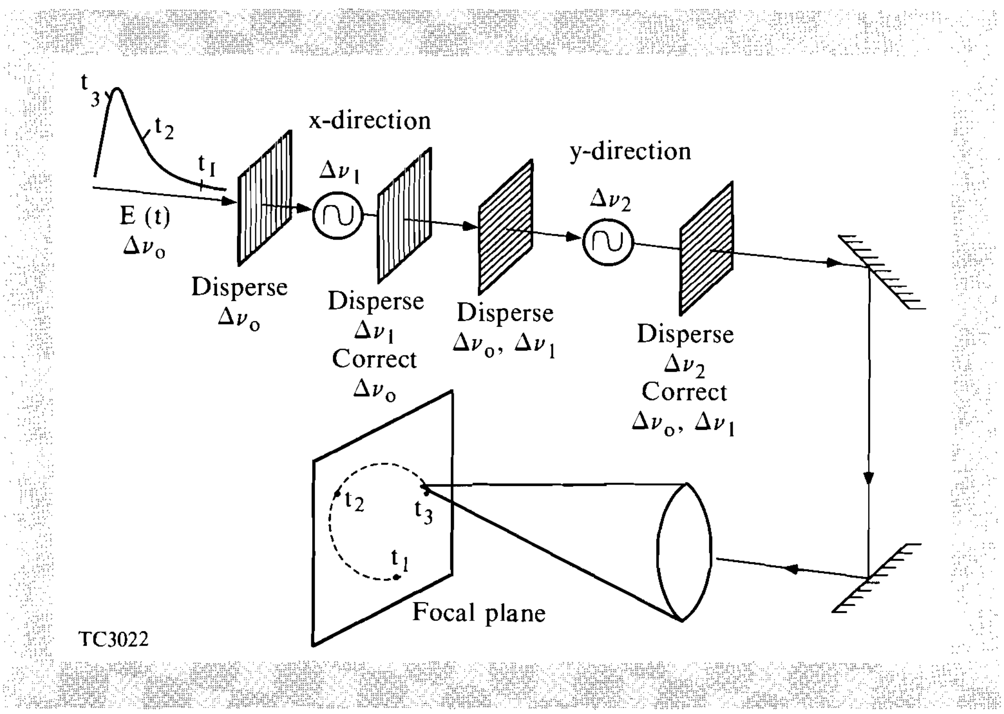

Fig. 50.16
An optical streak camera can be constructed using SBD. The gratings before and after each modulator assure that only the bandwidth imposed by that modulator will be deflected in the specified direction.

Bandwidth imposed by the first modulator will be dispersed in the x direction by the second grating, and then in the y direction by the third grating. But the y-direction dispersion is removed by the fourth grating, leaving this bandwidth dispersed only in the x direction. Bandwidth imposed by the second modulator will be dispersed only in the y direction by the fourth grating. Thus, when the beam is focused, it will trace out a pattern that includes deflection in both the x and y directions, determined only by the bandwidth from the two E-O modulators. For sinusoidal modulation, the beam will be deflected in a circle in the focal plane if the two bandwidths and modulation frequencies are equal, and if the relative phase differs by 90°. In general, any Lissajous pattern can be created.

The relative phase between the bandwidth imposed by the two modulators will vary across the beam because of time delays introduced by the second and third gratings. (This is the same kind of time delay that produces color cycling in SSD.) Thus, different parts of the beam can trace different patterns in the focal plane, and there will not be a unique "streak" for the entire beam. This effect can be small if the grating delay time is small compared to the modulation time of the bandwidth. Otherwise, it will be necessary to pass the beam through an aperture to isolate a portion of the beam for which the phase difference between the bandwidths is relatively constant.

It is not necessary to synchronize the modulators with respect to the peak of the pulse. The only constraint is that the modulation time should be longer than the pulse width so that the pulse will be displayed before the trace repeats itself. The position of the pulse in the focal plane will depend on the phase of the peak of the pulse, but it will not affect measurement of the beam's intensity variation as a function of time.

Examples of Pulse Shaping by SBD

Pulse shaping by SBD was modeled numerically. The bandwidth was decomposed into its spectral components. The spot size in the focal plane was taken into consideration when calculating the attenuation through the filter in the focal plane. The calculation includes the effects on shaping resolution based on spatial overlap of different spectral components and the effects of finite focal-spot size. The attenuated spectral distribution was recombined to determine the resulting waveform.

In the following examples, we consider the case where the focal-spot size was about 1/50 of the size of the beam-deflection region in the focal plane. We then find the amount of bandwidth required to achieve different pulse shapes.

The first example, Fig. 50.17, shows an attempt to numerically construct a high-order, 1-ns superGaussian pulse (the dashed line) using SBD. Figure 50.17(a) shows the effect of using only a small amount of bandwidth, 0.5 Å/ns. The shaped pulse is fairly well contained in the 1-ns region, but interference between different spectral components has produced intensity oscillations. As the bandwidth is increased in Figs. 50.17(b) and 50.17(c), the superGaussian shape is more clearly reproduced. The increased bandwidth makes the mapping between time and space more accurate so that in the focal plane there is less spatial overlap between different temporal regions.

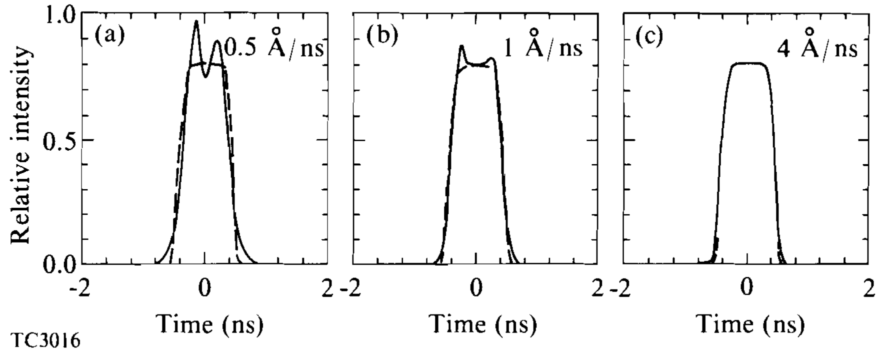

Fig. 50.17
A numerical simulation of SBD (solid line) to construct a high-order, 1-ns superGaussian pulse (dashed line). For low bandwidth (a) the pulse is well localized, but the time-space mapping is not sufficiently accurate to prevent interference between spectral components that produce intensity modulations. For higher bandwidth (c) greater temporal resolution is obtained. A laser wavelength of 1 µm was used, and the beam-deflection length in the focal plane is 50 times larger than the focal-spot diameter.

When the pulse shape is more gently rising, adequate resolution is obtained with less bandwidth. This is illustrated in Fig. 50.18 for a 7-ns pulse that could be used for laser-fusion experiments. Here only 2 Å is required. In the other extreme a more steeply rising pulse requires a higher bandwidth. Figure 50.19 shows the result of constructing a 250-ps superGaussian pulse. A bandwidth of 20 Å was required to produce a rise time of ~15 ps per decade, over four decades.

The effect of removing the bandwidth was also modeled by adding E-O bandwidth 180° out of phase. In all cases it was possible to eliminate or greatly reduce all excess bandwidth.

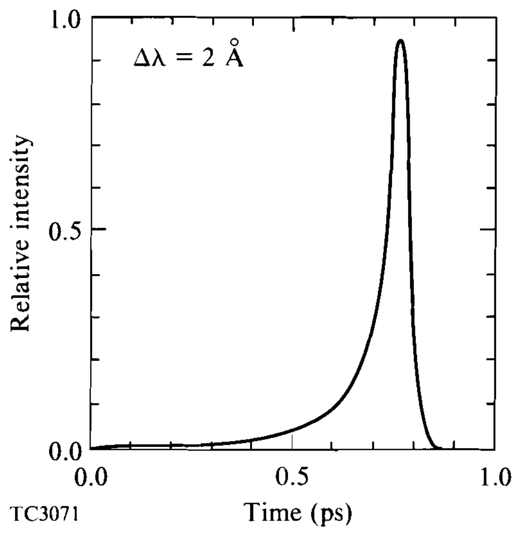

Fig. 50.18
For more gently rising pulses, less bandwidth is needed compared to Fig. 50.17.

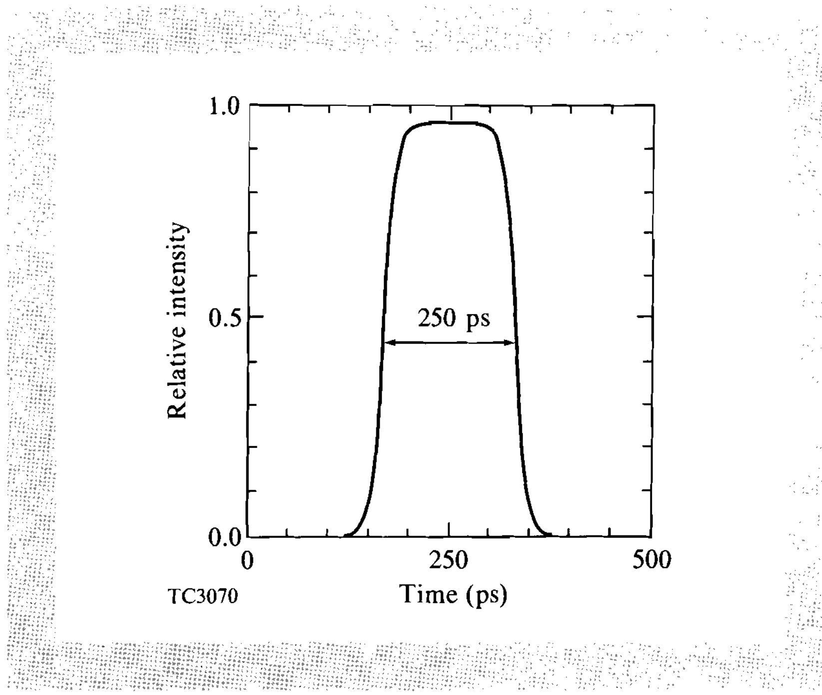

Fig. 50.19
For faster-rising pulses than in Fig. 50.17, larger bandwidth is required. A bandwidth of ~20 Å was required to produce a rise time of 15 ps/decade over a range of four decades.

Summary

Spectral beam deflection (SBD) is a very flexible technique for producing whole-beam deflection. This technique can provide a high-resolution mapping between time during the pulse and spatial position in the focal plane of a lens. Operating in the focal plane, we have the opportunity to modify the beam's temporal characteristics, using static amplitude filters, or to measure the beam's time history.

Four applications of SBD have been examined: (1) pulse shaping, (2) combining beam stretching with pulse shaping, (3) beam-size shaping, and (4) a design for an optical streak camera. Pulse shaping was modeled numerically to determine the effects on resolution from spectral overlap of different temporal regions and from spatial overlap caused by the finite spot size of the beam in the focal plane.

These techniques could be applied to several different areas. Spectral beam deflection can be used wherever laser scanning is required for illuminating objects and for reading and writing information very rapidly. Beam-size shaping might be used in machining or surgery for precision illumination of different portions of an object for different amounts of time. Precision pulse shaping could be used in optical-signal-processing applications.

ACKNOWLEDGMENT

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