Achromatic waveguide lenses

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An investigation of the chromatic properties of waveguide lenses is described. In general, the focal length of mode-index and Fresnel zone (diffractive) lenses will be a function of wavelength. As a result, these lenses will have high optical quality over only a relatively small wavelength range. A method is given to correct for this chromatic dispersion by forming a hybrid mode-index/diffractive doublet. Using this approach, the various lens parameters can be chosen so that the chromatic dispersion of the diffractive element will cancel the dispersion of the refractive element. In certain conditions, the power of the diffractive element in the hybrid achromatic doublet can be shown to go to zero producing an achromatic mode-index lens. It was found that, with typical waveguide materials, a 10-mm focal length, $f/5$ hybrid mode-index/diffractive lens can be made that has a usable wavelength range of ~80 nm. This is over an order of magnitude improvement compared with that obtained with conventional mode-index and diffractive lens types. *Key words*: Integrated optics, waveguide lenses, achromatization.

I. Introduction

Waveguide lenses are key components in many integrated optical devices such as spectrum analyzers,[1–5] signal correlators and convolvers,[6,7] fiber optic couplers,[8] and optical disk–pickup heads,[9–12] where they are used for tasks including focusing guided waves and taking Fourier transforms of signals created with acoustooptic (AO) Bragg cells. Many of these devices have been demonstrated in the prototype stage in a laboratory environment, but some of them have significant technological and manufacturing barriers to overcome before they reach high enough quality and reliability standards to be used in actual industrial applications.

One factor that limits the reliability, in some cases, is the performance stability of the device with variations in the wavelength of the light source. The wavelength variations may be due to multiplexing different wavelengths, thermal fluctuations of the source, or even the finite bandwidth of the source. Many of the components used in waveguide devices have an inherent chromatic dispersion that will cause the performance of the device to be a function of the source wavelength. In some devices, such as wavelength demultiplexers, this chromatic dispersion can be exploited to serve a useful purpose, but often it produces an undesirable degradation in the device performance. To make a device with the desired response characteristics, it is necessary either to precisely control the wavelength of the light or to achromatize the various components or cascade them so that the chromatic dispersions of the various elements will cancel each other. Until inexpensive wavelength-stabilized sources, such as distributed-feedback laser diodes, become readily available, the second option is much more attractive. In addition, this approach will permit the use of broadband or multiplexed sources as well as low cost (unstable) laser sources.

We have previously described a method to achromatize waveguide input/output couplers using a diffraction grating to cancel the inherent dispersion of these components.[13] This paper will explore similar ways to achromatize the response of waveguide lenses. In particular, we show that it is possible to correct the chromatic dispersion of a refractive (mode-index) lens with a properly chosen diffractive (Fresnel zone) lens. In Sec. II we first review the chromatic characteristics of the standard types of waveguide lens. In Sec. III we present a hybrid mode-index/diffractive waveguide lens that has an achromatic response over a broad wavelength interval around the design wavelength. In Sec. IV, we characterize the width of the achromatic wavelength range, and in Sec. V a discussion of the degrees of freedom which can be used to optimize this range is presented. The important results of this investigation are summarized in Sec. VI.

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II. Chromatic Properties of Standard Waveguide Lenses

Several methods have been used to make lenses in a waveguide system. These methods can be grouped loosely into four different categories: geodesic lenses, mode-index lenses, Luneburg lenses, and diffractive lenses.[14,15] Each of these types has significantly different chromatic characteristics. In fact, as we shall see, it is these very differences that suggest a way to combine different elements in a way so that the chromatic aberrations cancel each other.

A. Geodesic Lenses

Geodesic lenses are based on the concept of configuration lenses that was developed for the application of microwave antennas.[16,17] This approach was adapted to planar optical waveguides by Righini *et al.*[18] in 1972 and has been studied extensively since that time.[19–25] These lenses are made by forming a circularly symmetric depression in the substrate that changes the optical path length through which the light must travel, as shown in Fig. 1(a). Using Fermat's principle, the shape of the depression can be designed so that the ray paths will focus to a point. Although diffraction-limited performance can be obtained on-axis, these lenses have the disadvantage that they cannot be manufactured using standard photolithographic techniques. However, they have been used in prototypes for several devices because of their good performance and the ability to form these lenses on high index waveguides.[26–28] Since geodesic lenses work by physically changing the optical path length, all wavelengths of light will be focused in the same way, so that by nature they are achromatic. But despite this advantage, it is often desirable to consider other types of lens which can be made with planar photolithographic processes. This is particularly true since recent advances in integrated optics fabrication techniques have provided alternate methods of making other types of lens on high index waveguides.[29–31]

B. Mode-Index Lenses

The first waveguide lenses that were proposed and demonstrated were mode-index lenses.[32,33] These lenses work in much the same way that conventional glass optical elements do by using refraction at the boundary between two regions of different effective refractive indices. Ulrich and Martin[33] showed and experimentally demonstrated that light in a waveguide obeys the normal laws of geometrical optics (i.e., Fermat's principle and Snell's law), and, therefore, optical elements such as lenses and prisms can be designed in much the same way as in conventional optics. Mode-index lenses rely on a change in the effective mode index of the waveguide that can be obtained by either changing the thickness of the waveguide layer,[33,34] applying an overlay (or underlay) layer,[32,35] or changing the index of the waveguide layer itself using an ion-diffusion or ion-exchange technique[36–38] [see Fig. 1(b)]. The thickness-type mode-index lenses have a larger amount of scattering at the boundaries than do the ion-diffusion type, but this scattering can be substantially

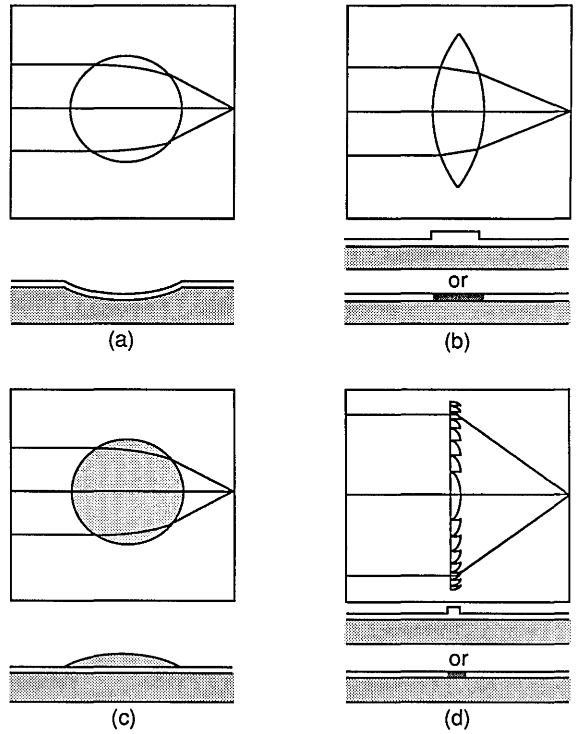

Fig. 1. Top and side views of standard types of waveguide lens: (a) geodesic, (b) mode index, (c) Luneburg, and (d) diffractive.

reduced by tapering the thickness at the boundary which acts effectively as an antireflection coating.[33] Mode-index lenses can easily be given acircular (analogous to aspherical) boundaries and can be grouped together to provide aberration correction.[38,39]

The response of a mode-index lens will in general change as a function of wavelength, because not only are the waveguide materials themselves dispersive, but in addition the effective mode index of a waveguide is a strong function of wavelength.[40] The changes in the mode indices will cause the ray paths through the lens to change and as a result will introduce aberrations which will be a function of the source wavelength.

In many cases, the most important wavelength dependence of a lens is longitudinal chromatic aberration. This is a variation of the image plane location with wavelength due to a change in the focal length of the lens. To first order, the optical power of a thin mode-index lens Φ_{mi} will be proportional to the difference in the effective index of refraction between the lens and background regions[41]:

$$\Phi_{mi}(\lambda) = C[N_L(\lambda) - N_B(\lambda)], \tag{1}$$

and the corresponding focal length F_{mi} will be given by

$$F_{mi}(\lambda) = \frac{N_B(\lambda)}{\Phi_{mi}(\lambda)} = \frac{N_B(\lambda)}{C[N_L(\lambda) - N_B(\lambda)]}, \tag{2}$$

where N_L and N_B are the effective mode indices of the lens and background regions (both being a function of wavelength), and C is a constant of proportionality related to the shape of the lens boundaries. The wavelength dependence of the effective mode indices can be either determined analytically from the material and waveguide parameters or measured experimentally for a desired waveguide configuration. For the purposes of this paper we neglect any anisotropic waveguide effects that may be present. For some waveguide materials there will be quite significant anisotropic aberrations,[42] and small adjustments will have to be made to account for them, but the basic concepts presented in this paper can be more clearly illustrated with isotropic waveguides.

Since in most integrated optics applications we are interested in relatively small wavelength intervals around some particular design wavelength, a good measure of the chromatic dispersion of a lens is the derivative of the focal length with respect to wavelength since this will indicate the magnitude of the chromatic variation in the neighborhood of the nominal wavelength. Differentiating Eq. (2) with respect to wavelength gives

$$\frac{dF_{\mathrm{mi}}(\lambda)}{d\lambda} = \frac{\Delta N(\lambda)\,\dfrac{dN_B(\lambda)}{d\lambda} - \Delta\left[\dfrac{dN(\lambda)}{d\lambda}\right] N_B(\lambda)}{C\Delta N(\lambda)^2}, \tag{3}$$

where we have defined

$$\Delta N(\lambda) \equiv N_L(\lambda) - N_B(\lambda), \tag{4}$$

$$\Delta\left[\frac{dN(\lambda)}{d\lambda}\right] \equiv \frac{dN_L(\lambda)}{d\lambda} - \frac{dN_B(\lambda)}{d\lambda}. \tag{5}$$

From Eq. (3) it can be seen that in general the derivative of the focal length will be nonzero, and, therefore, the lens will be dispersive.

For waveguide optical systems, it is desirable for the derivative of the focal length with respect to wavelength to be zero at the design wavelength; we will define this to be the achromatic lens condition. If this condition is met, then we expect the focal length to be essentially a constant in some interval around the nominal wavelength. This is somewhat different from the achromatic lens condition used in bulk optics where the focal length is equalized at two wavelengths on either side of the nominal wavelength (usually the *c*- and *f*-lines). In the case of integrated optics, we are usually only concerned with small fluctuations around some nominal wavelength, so equating the focal lengths at some other wavelengths does not tell us much about what is happening at the wavelength of interest. If the two wavelengths are chosen to be close to the design wavelength (say $\lambda_0 - \Delta\lambda$ and $\Delta_0 + \Delta\lambda$), it can easily be seen that as $\Delta\lambda$ goes to zero the conventional achromatic condition will be equivalent to setting the derivative equal to zero. The achromatic lens condition that we have defined can, therefore, be seen to be simply a limiting case of the conventional definition.

We can apply the achromatic lens condition to mode-index lenses by setting Eq. (3) equal to zero. We can then solve for the condition that will give an achromatic mode-index lens:

$$\frac{1}{N_L(\lambda_0)}\frac{dN_L(\lambda_0)}{d\lambda} = \frac{1}{N_B(\lambda_0)}\frac{dN_B(\lambda_0)}{d\lambda}, \tag{6}$$

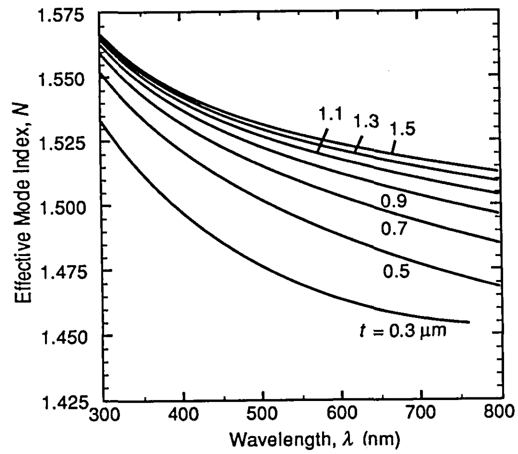

Fig. 2. Effective mode index for the TE_0 mode as a function of wavelength for various thicknesses t of a step-index Corning 7059 waveguide on an oxidized silicon substrate.

where λ_0 is the design wavelength. From Eq. (6), it can be seen that an achromatic mode-index lens will result if the relative index dispersion (the ratio of the mode-index derivative over the nominal mode-index value) of the lens and background regions are the same. For a given example, it may or may not be possible to design a mode-index lens that will satisfy this condition, depending on the waveguide material index characteristics and the waveguide fabrication process.

As an example, consider a thickness-type mode-index lens made on a step-index waveguide. The mode index as a function of wavelength is shown in Fig. 2 for different thicknesses of a typical waveguide material. These curves were made by solving the transcendental mode-index equation[40] for the mode index at each thickness and wavelength. The material dispersion characteristics used in the calculation of the data for this plot, and for the remainder of the figures in this paper, came from published data[43] and are summarized in Table I. From this figure it is apparent that both the effective mode index and the index dispersion (related to the slope of the curves) will be a function of the waveguide thickness.

A convenient plot to investigate the chromatic properties of a thickness-type lens is the relative index dispersion $(dN/d\lambda)/N$ as a function of the mode index N. This relationship is shown in Fig. 3 for the same waveguide materials as used in Fig. 2. From this curve, it can be observed that it is possible to pick pairs of thicknesses that have different mode indices but the same relative dispersion and, therefore, will satisfy Eq. (6). For example, if a waveguide were made with a thickness corresponding to A on Fig. 3 ($t_B = 0.35\ \mu$m), and a thickness-type mode-index lens were made on that waveguide corresponding to B ($t_L = 0.66\ \mu$m), the lens would satisfy the achromatic lens condition. Therefore, in certain conditions, it can be seen that an achromatic mode-index lens can be made by choosing an appropriate pair of mode indices. This fact has been noted by Ulrich and Martin.[33] In practice, however, it may not be possible or practical to choose an

Table I. Material Dispersion Characteristics Used in Calculations

Sellmeier formula: $n^2 = 1 + \sum_i \frac{A_i \lambda^2}{\lambda^2 - \lambda_i^2}$

Material	A_1	λ_1(μm)	A_2	λ_2(μm)	A_3	λ_3(μm)
SiO_2	0.6961663	0.0684043	0.4079426	0.1162414	0.8974794	9.896161

Least squares fit of tabulated data to Cauchy formula: $n = A_0 + A_1 \lambda^{-2} + A_2 \lambda^{-4}$

Material	A_0	A_1	A_2
7059 glass	1.51988	4.70006E-3	-2.38693E-5

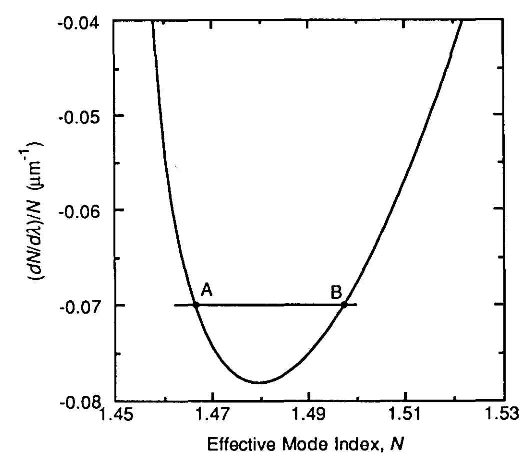

Fig. 3. Relative index dispersion of the TE_0 mode as a function of the effective mode index for a step-index Corning 7059 waveguide on an oxidized silicon substrate. The design wavelength is 0.6328 μm. Each point on the curve corresponds to a different waveguide thickness. Points A and B are an example of a pair of indices which would give an achromatic mode-index lens corresponding to waveguide thicknesses of 0.35 and 0.66 μm, respectively.

appropriate pair of mode indices in many cases. If there are constraints on the waveguide thicknesses due to manufacturing considerations, requirements of other components, the number of modes the waveguide should propagate, etc., or if other fabrication methods such as ion-exchange are used, it may not be feasible to choose the waveguide parameters so as to satisfy Eq. (6). In that case the achromatic lens condition would not be met, and the focal length of the lens would, therefore, not be constant in the wavelength interval around the design wavelength.

C. Luneburg Lenses

Luneburg lenses are very similar to mode-index lenses except that the thickness or overlay profile is tapered to produce continuous changes of the effective index profile [see Fig. 1(c)]. In this way they are the waveguide lens analogy to gradient-index lenses. This type of lens was first suggested by Zernike[44] and has been studied extensively since that time.[45–47] Conventionally these lenses have been round and circularly symmetric like the generalized Luneburg lenses in the field of gradient-index optics from which they get their name. Recently, however, this concept has been generalized to a rectangular shape as well.[48] Mode-index lenses with wide tapered edges can also be included in this general category since they have a gradient index near the lens boundaries. Luneburg lenses have the advantage over thickness-type mode-index lenses that they have reduced scattering at the lens boundary because of the gradual change in the thickness rather than the abrupt jump. They have the disadvantage, however, that they cannot be made with standard photolithographic techniques. Since the dispersion characteristics of the waveguide, as well as the mode index, will change continuously as the thickness changes, the dispersion characteristics of this lens are quite complex to model. Except possibly in some special cases, it would be necessary to use a ray tracing program to determine the focusing characteristics of this type of lens as a function of wavelength. It may be possible by optimizing the shape of the thickness profile to obtain a Luneburg lens that meets the achromatic lens condition, but that problem is not addressed here.

D. Diffractive Lenses

Although the terminology used in the literature is far from consistent, diffractive lenses in integrated optics can be put into two cateogries: chirped-grating lenses[49–53] and blazed Fresnel zone lenses.[54–58] Both types utilize a Fresnel zone structure to diffract the light and obtain focusing and can be made with planar photolithographic manufacturing techniques.

Lenses in the first category consist of a Bragg grating whose frequency is linearly chirped with the distance from the optical axis. They would be analogous to thick holographic lenses in conventional diffractive optics. The index modulation can either be in sharp steps or have a sinusoidal profile, and the grating lines are often tilted or curved to increase the on-axis diffraction efficiency.

Blazed Fresnel zone waveguide lenses are the integrated optics equivalent of kinoform lenses.[59,60] These lenses are thin phase gratings, where the zones are blazed to give a segmented continuous phase profile [see Fig. 1(d)]. In the literature these lenses have frequently been called simply Fresnel lenses, but this terminology leads to confusion with the conventional Fresnel lenses, which are commonly used in devices such as overhead projectors. Those lenses are made of concentric prismlike rings, which are designed to refract the light to the desired focus position. Since that type of lens does not use diffraction phenomenon at all (in fact they are designed to avoid diffraction effects), the term Fresnel lens should not be used to describe Fresnel zone lenses which are purely diffractive. We, therefore, suggest that waveguide kinoform lenses or blazed Fresnel zone lenses is more appropriate terminology.

Waveguide kinoform lenses can be made with either graded-index (GRIN) or graded-thickness (GRTH) techniques. Kinoform lenses of both types have been demonstrated with near diffraction-limited performance on-axis.[54,56,57] Kinoform lenses have the advantage of higher efficiency, a wider angle of acceptance, as well as a larger spectral bandwidth compared with chirped-grating lenses. Because of these factors, kinoform lenses have been used much more frequently than chirped-grating lenses in recent years. The chirped-grating lenses, however, are easier to manufacture at small grating pitches, and this has recently led to the development of hybrid lenses that are of the kinoform type in the center region of the lens where the zone spacing is large and use a chirped-grating structure near the edges where the zone spacing is small.[58,61]

All types of diffractive lens are, however, by their nature highly wavelength dependent. Many characteristics of these lenses, such as their aberrations and diffraction efficiency, will be functions of wavelength. One of the most important chromatic effects is the strong wavelength dependence of the optical power. As with conventional diffractive lenses, it can easily be shown that the optical power will be proportional to the wavelength of the light:

$$\Phi_d(\lambda) = \left(\frac{\lambda}{\lambda_0}\right)\Phi_{d0}, \tag{7}$$

where Φ_{d0} is the power at the design wavelength λ_0. The focal length F_d will, therefore, be given by

$$F_d(\lambda) = \frac{N_B(\lambda)}{\Phi_d(\lambda)} = \frac{\lambda_0}{\lambda}\frac{N_B(\lambda)}{N_{B0}}F_{d0}, \tag{8}$$

where $N_{B0} = N_B(\lambda_0)$ and $F_{d0} = N_{B0}/\Phi_{d0}$. The chromatic dispersion is found by simply taking the derivative of the focal length:

$$\frac{dF_d(\lambda)}{d\lambda} = \frac{\lambda_0 F_{d0}}{N_{B0}}\frac{\lambda\frac{dN_B(\lambda)}{d\lambda} - N_B(\lambda)}{\lambda^2}. \tag{9}$$

Evaluating Eq. (9) at the design wavelength we find that

$$\frac{dF_d(\lambda_0)}{d\lambda} = \frac{F_{d0}}{N_{B0}}\left[\frac{dN_B(\lambda_0)}{d\lambda} - \frac{N_B(\lambda_0)}{\lambda_0}\right]. \tag{10}$$

From this equation, it can be seen that the dispersion of a diffractive lens will be proportional to the nominal focal length of the lens, and the constant of proportionality is just a function of the waveguide material parameters. If a diffractive lens is to satisfy the achromatic lens condition, $dF_d(\lambda_0)/d\lambda$ in Eq. (10) must equal zero, which would then imply that

$$\frac{dN_B(\lambda_0)}{d\lambda} = \frac{N_B(\lambda_0)}{\lambda_0}. \tag{11}$$

The dispersion of the mode index that is required to satisfy this equation would be positive, but the derivative of the index will be negative in a real waveguide, as is demonstrated in Fig. 2. Therefore, it is not possible to make an achromatic diffractive waveguide lens. Relative to other waveguide lenses, diffractive lenses usually have a large amount of chromatic dispersion. Because of this, waveguide devices that have used these lenses typically require relatively tight wavelength control.

III. Hybrid Mode-Index/Diffractive Achromat

Both the mode-index and diffractive types of waveguide lens are practical to make with planar waveguide technology and are, therefore, desirable from a manufacturing standpoint. However, as we have seen, they both in general suffer from chromatic aberrations. In special cases, mode-index lenses can be made that have no chromatic dispersion, but many times this may not be a practical solution, particularly when ion-exchange fabrication techniques are used. This leads us to look for other ways to eliminate the chromatic aberrations.

The usual way to correct chromatic aberrations in conventional (or bulk) optics is to use two or more elements made of glasses with different dispersions.[62] The optical power of the different elements can then be balanced so that the total power at a select number of wavelengths is equal. It has been suggested that this approach could be used with waveguide mode-index lenses also by making multiple lens elements with different thicknesses and, therefore, different mode indices and dispersions.[33] This method would be quite complex to manufacture and in many cases, such as with ion-exchange lenses, would probably not be feasible at all. Even if there were enough freedom to choose the waveguide thicknesses to make this approach possible, it would probably be just as easy to choose the proper thicknesses to make a single-element mode-index achromat as described in Sec. II.

Another technique to correct the chromatic dispersion in conventional optics that has been of interest recently is the combining of refractive and diffractive elements to form hybrid optical systems.[59,63–69] In these schemes, the dispersion of the glass elements and the diffractive elements is balanced so that the resulting combination is achromatic. One approach that is particularly attractive for adaptation to waveguide lenses is the method of forming an achromatic doublet (or a doublet with arbitrary dispersion) by combining a single refractive element with a diffractive element. Using this scheme, it has been shown that it is possible to correct the response exactly at two wavelengths and reduce the chromatic aberrations significantly over a broad spectral region.[67]

For waveguide lenses, the problem is usually slightly different, in that the wavelength range that we need to correct over is much smaller than the entire visible spectrum—typically it is only of the order of 20 nm or less. Because of this, a different approach is used in the design of an achromatic diffractive/refractive waveguide lens. Rather than designing the lens to have equal powers at two different wavelengths, it is more appropriate to design it so that the derivative of the lens focal length is zero at the design wavelength—this is the achromatic lens condition that we introduced earlier. Meeting this condition will insure that the chromatic dispersion of the doublet will be minimized in the wavelength interval around the design wavelength.

To illustrate this principle, consider a doublet made of a mode-index lens and a diffractive lens. Although the doublet could be made with two separate elements, they could also be combined into a single hybrid component as shown in Fig. 4. This configuration would seem to be quite attractive since there are only two boundaries where scattering will occur, and, therefore, the insertion loss should not be significantly greater than for either a single mode-index or a diffractive lens. The total power Φ_T of the doublet will be approximately equal to the sum of the powers for each element if the thickness is small:

$$\Phi_T(\lambda) \approx \Phi_{mi}(\lambda) + \Phi_d(\lambda). \tag{12}$$

Substituting from Eqs. (1), (4), and (7), we find that

$$\Phi_T(\lambda) = C\Delta N(\lambda) + \left(\frac{\lambda}{\lambda_0}\right)\Phi_{d0}. \tag{13}$$

The focal length of the doublet is, therefore, given by

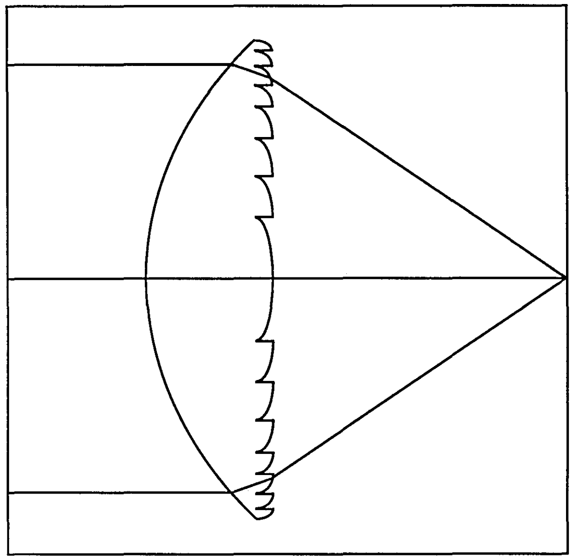

Fig. 4. Possible configuration for hybrid mode-index/diffractive achromat.

$$F_T(\lambda) = \frac{N_B(\lambda)}{\Phi_T(\lambda)} = \frac{N_B(\lambda)}{C\Delta N(\lambda) + \left(\frac{\lambda}{\lambda_0}\right)\Phi_{d0}}. \tag{14}$$

Now, taking the derivative of this equation with respect to wavelength, we obtain an expression for the chromatic dispersion:

$$\frac{dF_T(\lambda)}{d\lambda} = \frac{\left[C\Delta N(\lambda) + \left(\frac{\lambda}{\lambda_0}\right)\Phi_{d0}\right]\frac{dN_B(\lambda)}{d\lambda} - \left[C\Delta\left(\frac{dN(\lambda)}{d\lambda}\right) + \frac{\Phi_{d0}}{\lambda_0}\right]N_B(\lambda)}{\left[C\Delta N(\lambda) + \left(\frac{\lambda}{\lambda_0}\right)\Phi_{d0}\right]^2}. \tag{15}$$

To satisfy the achromatic lens condition we set $dF_T(\lambda)/d\lambda$ in Eq. (15) equal to zero when $\lambda = \lambda_0$, which gives

$$[C\Delta N(\lambda_0) + \Phi_{d0}]\frac{dN_B(\lambda_0)}{d\lambda}\left\{C\Delta\left[\frac{dN(\lambda_0)}{d\lambda}\right] + \frac{\Phi_{d0}}{\lambda_0}\right\}N_B(\lambda_0) = 0. \tag{16}$$

Likewise, evaluating Eq. (13) at $\lambda = \lambda_0$ gives the nominal total power:

$$\Phi_{T0} = \Phi_T(\lambda_0) = C\Delta N(\lambda_0) + \Phi_{d0}. \tag{17}$$

We can now solve Eqs. (16) and (17) for C and Φ_{d0}, giving the nominal powers of the mode-index and diffractive lenses that will produce an achromatic doublet with the desired total power:

$$\Phi_{mi0} = C\Delta N(\lambda_0) = \Phi_{T0}\frac{\Delta N(\lambda_0)}{N_B(\lambda_0)}\left\{\frac{\frac{dN_B(\lambda_0)}{d\lambda} - \frac{N_B(\lambda_0)}{\lambda_0}}{\Delta\left[\frac{dN(\lambda_0)}{d\lambda}\right] - \frac{\Delta N(\lambda_0)}{\lambda_0}}\right\}, \tag{18}$$

$$\Phi_{d0} = \frac{\Phi_{T0}}{N_B(\lambda_0)}\left\{\frac{N_B(\lambda_0)\Delta\left[\frac{dN(\lambda_0)}{d\lambda}\right] - \frac{dN_B(\lambda_0)}{d\lambda}\Delta N(\lambda_0)}{\Delta\left[\frac{dN(\lambda_0)}{d\lambda}\right] - \frac{\Delta N(\lambda_0)}{\lambda_0}}\right\}. \tag{19}$$

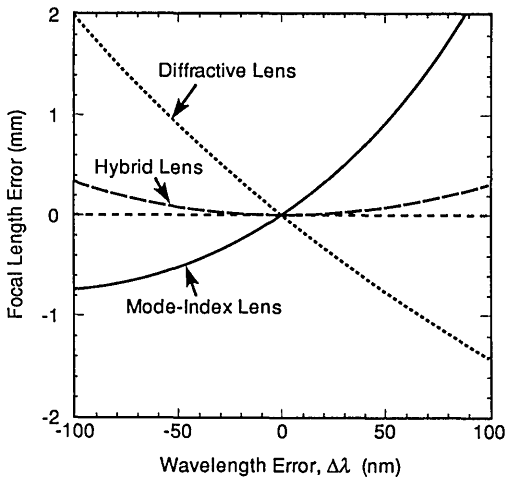

Fig. 5. Comparison of longitudinal chromatic aberration (wavelength dependent focal length errors) for conventional mode-index and diffractive lenses and a hybrid mode-index/diffractive achromat. The simulated waveguide consisted of a 0.5-μm layer of Corning 7059 glass on an oxidized silicon substrate giving a TE_0 mode index of 1.484 at $\lambda_0 = 0.6328$ μm. The mode-index lens elements were formed by reducing the thickness to 0.3 μm to give a mode-index difference of $\Delta N(\lambda_0) = -0.024$. All three lenses were designed to be $f/5$ and have a nominal focal length of 10 mm.

This approach allows us to design an achromatic waveguide lens for a system with arbitrary dispersion characteristics for the waveguide and lens regions. Note that if the condition for an achromatic mode-index lens that was given in Eq. (6) is met, it follows from Eqs. (18) and (19) that, as expected, $\Phi_{\mathrm{mi}0} = \Phi_{T0}$ and $\Phi_{d0} = 0$, so that all the power is in the mode-index lens. Thus the achromatic mode-index lens described in Sec. II.B can be regarded as a special case of the hybrid mode-index/diffractive achromatic lens.

The spectral characteristics of this achromatic lens design are illustrated in Fig. 5. The longitudinal chromatic aberration of a hybrid mode-index/diffractive waveguide lens is compared with that of the conventional lens types for typical waveguide materials (Corning 7059 glass on an oxidized silicon substrate). The lenses in each case were designed to have a focal length of 10 mm and to be $f/5$. The material dispersion characteristics used in these calculations are given in Table I. The nominal powers of the mode index and diffractive elements for the achromatic doublet were found using Eqs. (18) and (19), giving focal lengths of $F_{\mathrm{mi}}(\lambda_0) = 18.4$ mm and $F_d(\lambda_0) = 21.9$ mm, respectively. Note that since the index change is negative for this example the lens boundary for the mode-index element will be concave rather than convex as shown in Fig. 4 to obtain a positive focal length. The chromatic dependence of the focal lengths of the different lens was calculated using Eqs. (2), (8), and (14). It can be observed that not only is the focal length of the achromatic doublet essentially a constant over small wavelength errors as expected, but the total focal length error is much smaller than that of the mode-index and diffractive singlets over the entire range of wavelength errors considered.

For certain applications, such as those which use multiple wavelengths of light, the conventional definition of an achromatic lens may be more appropriate. For this case, we want to have the focal length of the lens be equivalent at two different wavelengths, say λ_1 and λ_2. Substituting these wavelengths into Eq. (14) and defining the desired focal length to be F_{T0}, we obtain the following equations:

$$F_T(\lambda_1) = F_{T0} = \frac{N_B(\lambda_1)}{C_2\Delta N(\lambda_1) + \left(\frac{\lambda_1}{\lambda_0}\right)\Phi_{d0,2}}, \tag{20}$$

$$F_T(\lambda_2) = F_{T0} = \frac{N_B(\lambda_2)}{C_2\Delta N(\lambda_2) + \left(\frac{\lambda_2}{\lambda_0}\right)\Phi_{d0,2}}. \tag{21}$$

In these equations, subscript 2 of the mode-index constant and the nominal diffractive lens power indicate that they correspond to this second type of achromatic lens condition. As before we can now solve these two equations for the nominal power of the refractive and diffractive components that will yield the desired achromatic condition:

$$\Phi_{\mathrm{mi}0,2} = C_2\Delta N(\lambda_0) = \frac{\Delta N(\lambda_0)}{F_{T0}}\left[\frac{\lambda_2 N_B(\lambda_1) - \lambda_1 N_B(\lambda_2)}{\lambda_2\Delta N(\lambda_1) - \lambda_1\Delta N(\lambda_2)}\right], \tag{22}$$

$$\Phi_{d0,2} = \frac{\lambda_0}{F_{T0}}\left[\frac{N_B(\lambda_2)N_L(\lambda_1) - N_B(\lambda_1)N_L(\lambda_2)}{\lambda_2\Delta N(\lambda_1) - \lambda_1\Delta N(\lambda_2)}\right]. \tag{23}$$

Note that the nominal powers given by Eqs. (22) and (23) are specified at some wavelength λ_0, which may or may not be taken to be one of the two design wavelengths, λ_1 and λ_2. This result may be useful for some specific cases, but in general, when a small range of wavelengths is being considered, the first solution we obtained should be more valuable. Therefore, although we present this solution for completeness, for the remainder of this paper we consider only the first achromatic lens condition that required the derivative of the focal length to be zero.

IV. Calculation of the Achromatic Wavelength Range

The achromatic lens condition that we have defined insures that the focal length will be essentially a constant in some interval around the design wavelength, but we have not said anything about how large that interval might be. This section addresses this question for both uncorrected and achromatic waveguide lenses. For simplicity, we assume an infinitely distant on-axis object being imaged to the focal plane corresponding to the nominal wavelength, although it could be generalized to any object distance in a straightforward manner. For these calculations we assume that the only aberration present is longitudinal chromatic aberration, which is a wavelength dependent defocus due to the change in focal length. This is a reasonable assumption since the contour of the mode-index lens can be made acircular, and the zone spacing of the diffractive lens can be chosen accordingly to give diffraction-limited performance on-axis for the nominal

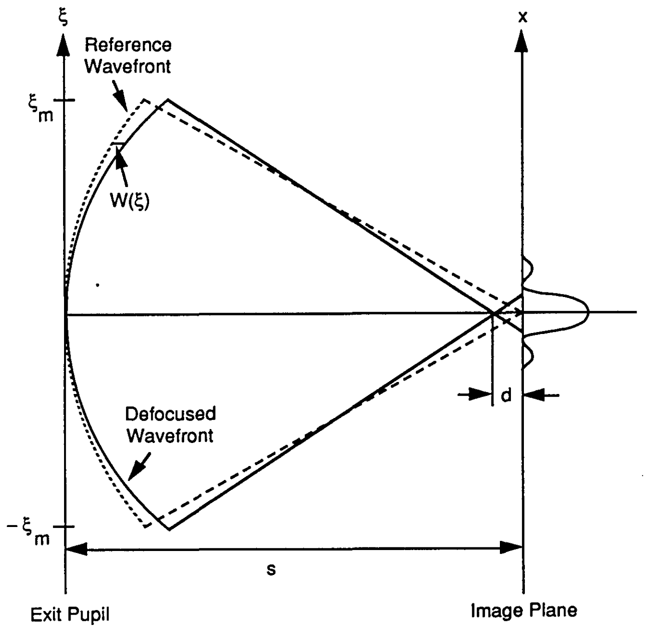

Fig. 6. Notation used for point spread function calculation: s is the distance from the exit pupil to the paraxial image plane, ξ_m is the halfwidth of the exit pupil, and d is the defocus amount. $W(\xi)$ is the difference between the reference circle and the aberrated wavefront.

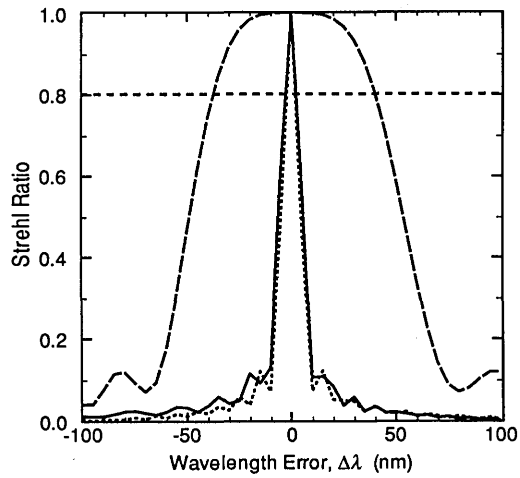

Fig. 7. Strehl ratio as a function of wavelength error for conventional mode-index (solid curve) and diffractive (dotted curve) lenses and the hybrid mode-index/diffractive achromat (dashed curve). The simulated waveguide consisted of a 0.5-μm layer of Corning 7059 glass on an oxidized silicon substrate giving a mode index of 1.484 at $\lambda_0 = 0.6328$ μm for the TE_0 mode. The mode-index lens elements were formed by reducing the thickness to 0.3 μm to give a mode-index difference of $\Delta N(\lambda_0) = -0.024$. All three lenses were designed to be $f/5$ and have a nominal focal length of 10 mm. The line at a Strehl ratio of 0.8 indicates the generally accepted limit for near diffraction-limited performance.

wavelength. There will be higher-order chromatic aberrations in a real lens, but in general they will be much smaller than the error due to defocus. The problem, therefore, reduces to determining first how large a defocus can be tolerated and second what wavelength error corresponds to the limiting focus error.

There are several possible image quality metrics that could be used to determine the limit of acceptable aberrations for a lens system, such as spot size, encircled energy, or Strehl ratio. For our analysis we have chosen the Strehl ratio as the basis of the limiting defocus calculation. This quantity is defined to be the ratio of the central intensity of the aberrated point spread function to that of the diffraction-limited point spread function. A generally accepted limit on the Strehl ratio for near diffraction-limited performance is that the magnitude should be greater than or equal to 0.8. To determine the amount of defocus necessary to reduce the Strehl ratio to this value, we need an expression for the point spread function of a defocused system. From the Rayleigh-Sommerfeld diffraction formula with the usual paraxial approximations it can be shown that the field at the paraxial focus point of a converging spherical wave with a wavefront aberration function W is given by

$$U(x) = A \int_{-\xi_m}^{\xi_m} \exp\left\{-i \frac{2\pi}{\lambda}\left[\frac{x\xi N_B}{s} + W(\xi)\right]\right\} d\xi, \tag{24}$$

where the various quantities in this equation are identified in Fig. 6. For a lens with pure defocus it can be shown that[70]

$$W(\xi) \approx a_1\left(\frac{\xi}{\xi_m}\right)^2, \tag{25}$$

where

$$a_1 \approx -\frac{N_B d}{2}\left(\frac{\xi_m}{s}\right)^2. \tag{26}$$

Since the Strehl ratio only involves the central intensity, we set x equal to zero in Eq. (24) to give

$$U(0) = \frac{\int_{-\xi_m}^{\xi_m} \exp\left[-i \frac{2\pi}{\lambda} W(\xi)\right] d\xi}{\int_{-\xi_m}^{\xi_m} d\xi}, \tag{27}$$

where for convenience the constant A has been chosen to give unit field amplitude when $W(\xi) = 0$. Since it is normalized, the magnitude squared of this expression is just the Strehl ratio which is the desired result. Equation (27) was evaluated using numerical integration techniques to calculate the Strehl ratio for the examples given earlier in Fig. 5. The focal length error d at each wavelength was converted to a wavefront aberration using Eqs. (25) and (26), and the resulting wavefront error was substituted into Eq. (27). The results of these calculations are shown in Fig. 7. The intensity point spread function was also calculated in each case using Eq. (24) to find the full width at half-maximum (FWHM) spot size. These results are shown in Fig. 8. Note from these two figures that the defocus values that give a Strehl ratio equal to the 0.8 threshold value in Fig. 7 correspond closely to the onset of the rapid spot size growth in Fig. 8, which confirms that the Strehl ratio is a useful metric for determining aberration tolerances. Note that the slight slope in the valley of the spot-size curve for the achromatic lens occurs because the diffraction-limited

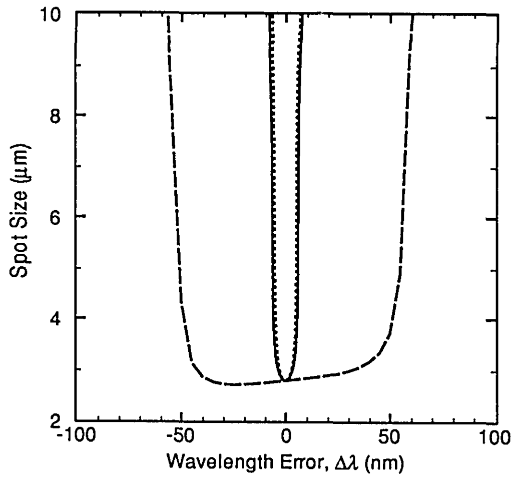

Fig. 8. Spot size (FWHM) as a function of wavelength error for conventional mode-index (solid curve) and diffractive (dotted curve) lenses and the hybrid mode-index/diffractive achromat (dashed curve). The simulated waveguide consisted of a 0.5-μm layer of Corning 7059 glass on an oxidized silicon substrate giving a mode index of 1.484 at $\lambda_0 = 0.6328\ \mu$m for the TE_0 mode. The mode-index lens elements were formed by reducing the thickness to 0.3 μm to give a mode-index difference of $\Delta N(\lambda_0) = -0.024$. All three lenses were designed to be $f/5$ and have a nominal focal length of 10 mm.

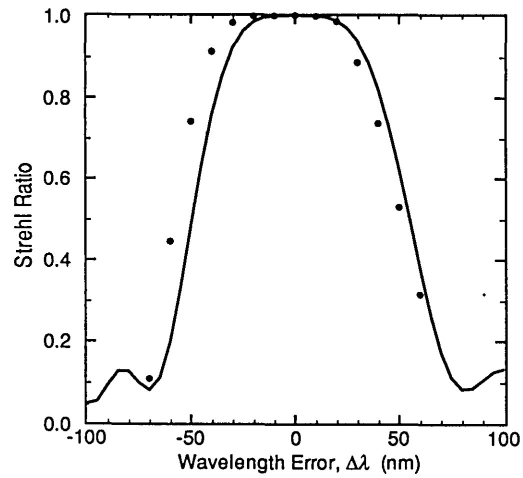

Fig. 9. Comparison of the Strehl ratio calculated using the defocus-only assumption (solid curve) with results of the exact ray trace (solid circles) for a hybrid mode-index/diffractive achromat. The simulated waveguide consisted of a 0.5-μm layer of Corning 7059 glass on an oxidized silicon substrate. The mode-index lens element was formed by reducing the thickness to 0.3 μm. The lens was designed to be $f/5$ and have a nominal focal length of 10 mm. The exact ray trace data were generated using the program Super-Oslo.

spot size is a function of wavelength and not because of any change in the spot quality. In both of these figures, the advantage of the achromatic doublet is very obvious. The wavelength range where the Strehl ratio is above threshold for both of the conventional lenses is ~6 nm, whereas for the hybrid mode-index/diffractive lens the wavelength range is ~78 nm. This is over an order of magnitude improvement in the usable wavelength range for this example. It should be noted that since the depth of focus of a lens is a strong function of the pupil diameter, these ranges could be increased substantially by using larger f/No. lenses.

To confirm that the assumption that we can ignore all the aberrations except for the longitudinal color when calculating the performance characteristics of these lenses is valid, the design for the achromatic doublet used in Figs. 7 and 8 was analyzed using exact ray trace methods in the lens design program Super-Oslo.[71] The mode-index dispersion relationships were calculated for the background and lens regions, and the data were fit to the standard dispersion polynomial for use in the program. The diffractive lens element was simulated by using a thin lens with an extremely large index of refraction as described by Sweatt[72] and Klienhans.[73] The power of the mode index and diffractive elements given by Eqs. (18) and (19) had to be adjusted slightly to correct for the nonzero separation. The conic constant of the mode-index boundary was chosen to correspond to the value which would give diffraction-limited focusing for a single refractive surface {c.c. = $-[N_B(\lambda_0)/N_L(\lambda_0)]^2$}, and the conic constant of the diffractive element was chosen using the Super-Oslo optimization algorithm to eliminate all spherical aberration at the nominal wavelength. The program was then used to calculate both the Strehl ratio and the

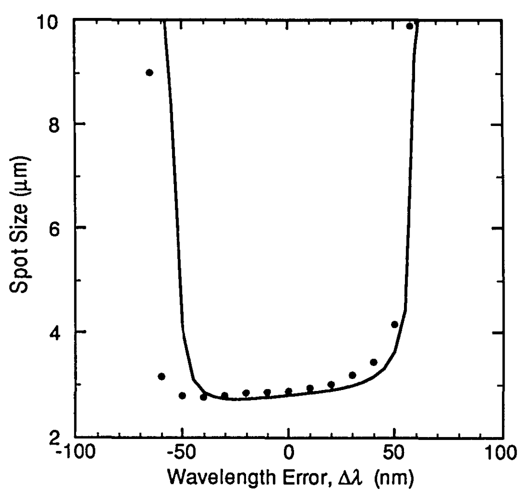

Fig. 10. Comparison of the FWHM spot size calculated using a defocus-only assumption (solid curve) with results of an exact ray trace (solid circles) for a hybrid mode-index/diffractive achromat. The simulated waveguide consisted of a 0.5-μm layer of Corning 7059 glass on an oxidized silicon substrate. The mode-index lens element was formed by reducing the thickness to 0.3 μm. The lens was designed to be $f/5$ and have a nominal focal length of 10 mm. The exact ray trace data were generated using the program Super-Oslo.

spot size as a function of wavelength error. The results of these calculations are shown in Figs. 9 and 10. The figures show excellent agreement between the exact ray trace data and the results from the previous defocus-only calculations validating our assumption. Note that for negative wavelength errors the actual performance is slightly better than the first-order approximation, and for positive errors the actual performance is slightly worse. This is due to a small amount of spherochromatism, which balances some of the defocus in one direction and adds to the aberrations in the other,[62] but overall it does not significantly affect the wavelength range. Again, it should be noted here that any anisotropic effects have been ignored for the purposes of this example. For some real waveguides it will be important to include these effects when performing the actual lens design and calculating the lens performance.

It should be noted that in calculating the wavelength ranges in this section we have not considered any diffraction efficiency effects. For diffractive lenses, the diffraction efficiency will peak at the design wavelength and will fall off as the wavelength detuning grows. For chirped Bragg grating-type lenses this efficiency decline is rather rapid, but for the kinoform-type diffractive lenses the efficiency bandwidth is quite large. Typically the range of wavelengths where the diffraction efficiency is >50% is in the hundreds of nanometers. Since the wavelength range limited by the longitudinal chromatic aberration discussed in this section has been substantially less than this for the examples we have considered, the diffraction efficiency should not be an important factor. However, if it is found for other cases that the chromatic aberrations can be reduced over a larger wavelength range it may be necessary to consider diffraction efficiency losses.

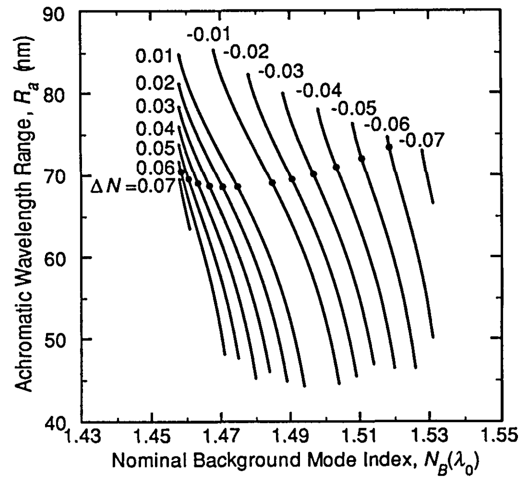

Fig. 11. Achromatic wavelength range of hybrid mode-index/diffractive achromatic lens as a function of the background mode index for a series of different ΔN values. The simulated waveguide was Corning 7059 glass on an oxidized silicon substrate, and the nominal wavelength was $\lambda_0 = 0.6328$ μm. The desired mode indices were obtained by choosing the appropriate thickness of the waveguide layer. The lenses were designed to be $f/5$ and have a nominal focal length of 10 mm. For each configuration, the power of the mode-index and Fresnel components was chosen using Eqs. (18) and (19) to satisfy the achromatic lens condition. The solid points on the curves indicate the locus of points where the lens is purely of the mode-index type.

V. Optimization of the Hybrid Mode-Index/Diffractive Achromat

In the previous section, the concept of an achromatic wavelength range was introduced for the hybrid mode-index/diffractive achromatic doublet. For a given waveguide configuration, the wavelength range will be fixed since it is a function only of the mode-index dispersion of the background and lens regions and the focal length and f/No. of the lens. For some waveguide fabrication techniques, such as titanium-indiffused proton-exchanged lenses on a $LiNbO_3$ substrate, there will be only a small amount of freedom to control the mode-index dispersions. However, for lenses made with thickness-type fabrication techniques the dispersions will be strongly dependent on the thicknesses which are used. This leads then to the question as to whether there is some optimum configuration which will maximize the achromatic wavelength range of the lens. For given waveguide materials, the two degrees of freedom that we have are the thicknesses of the background and lens regions. These will accordingly determine the background effective mode index and the ΔN value associated with the lens as well as the dispersion of the two regions.

Curves illustrating the relationship between the achromatic wavelength range and these two parameters are shown in Fig. 11 for common waveguide materials. The range of values plotted on the curves was truncated when the effective f/No. of one of the two elements of the hybrid lens went below $f/1$ and by the cutoff thickness for the guided mode. The solid circles indicate the locus of the points where Eq. (6) is satisfied, and, therefore, the lens is purely mode index. Moving to the left along one of the constant ΔN curves will decrease the power of the mode-index element and increase the power in the diffractive element. Moving to the right will increase the power of the mode-index element and give an increasingly negative power to the diffractive element. Therefore, in this example, for a given ΔN it is desirable to use the minimum practical background mode index, because in addition to increasing the achromatic wavelength range, it will also balance the power in the two elements, therefore, reducing the curvature of the mode-index lens boundaries. Since only a fraction of the power of the doublet will reside in the diffractive element, the minimum zone spacing required is typically much larger than a single diffractive lens, which, therefore, makes fabrication of that element easier as well. Considering only the achromatic wavelength range, it can be seen from Fig. 11 that in this case there is not a great advantage in using a hybrid doublet over a purely mode-index lens where the indices are properly chosen to meet the achromatic lens condition. But the use of the hybrid doublet increases the flexibility for the waveguide design parameters since a much wider range of mode-index pairs could be used. This may make fabrication and integration with other waveguide components easier. This flexibility also allows the power of the individual mode-index and diffractive lens elements to be reduced permitting larger diameter lenses and, therefore, a smaller effective f/No. for the lens pair. To optimize the design for a specific application will, therefore, involve taking into account the various device and waveguide material constraints as well as any limits to the fabrication process.

VI. Conclusions

We have reviewed the chromatic properties of the conventional types of waveguide lens. It has been shown that although both mode-index and diffractive waveguide lenses have in general substantial chromatic dispersion, they can be combined to form a hybrid achromatic doublet. A special case of the hybrid lens occurs when the condition specified in Eq. (6) is met, giving an achromatic mode-index lens. In general, it has been shown that the use of a hybrid achromatic lens should increase the usable wavelength range for the lens by as much as an order of magnitude over the conventional mode-index or diffractive lens types. It should be possible to make these hybrid lenses using any of the standard waveguide fabrication techniques that have been used to make mode-index and diffractive lenses. In fact, since the power in the individual elements is quite often lower than that of a single conventional lens, the fabrication may be easier due to reduced curvatures and larger zone spacings. The magnitude of the achromatic range that has been shown to be possible suggests that these lenses could be used not only to correct for random fluctuations in the wavelength of a single wavelength source but also for broadband or multiple wavelength sources as well.

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