Design, assembly, and testing of an objective lens for a free-space photonic switching system

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Abstract. The design, assembly, and testing details of an objective lens used to image an array of 4096 beams are discussed. The main characteristics of the lens are a 15-mm focal length, a speed of $f/1.5$, diffraction-limited quality, telecentricity, f-sin(θ) mapping, an external stop, and a simplicity of fabrication.

Subject terms: lens design; lens manufacturing; lens testing; photonic switching.

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1 Introduction

Free-space optical switching and computing systems utilize macroscopic optical elements such as holograms, gratings, lenses, and mirrors as their basic hardware building blocks. In these systems, information is carried by arrays of beams of light that are collimated, manipulated, and focused onto spatial light modulators (SLMs) in a stage-by-stage fashion. The photonics switching work at AT&T Bell Laboratories has involved the fabrication of several prototype systems[1–8] with increasing complexity and functionality. The motivation in developing free-space optical switching systems is the opportunity offered by optics to interconnect a large number of communication channels at a high bit rate. There are various engineering issues involved in a practical optical system for switching and computing. In this paper, the design, assembly, and testing of a lens for a free-space multistage optical switching system capable of manipulating an array of 4096 beams are discussed.

2 Lens Requirements

An optical layout illustrating the basic elements of a free-space optical switching stage is presented in Fig. 1. The initial array of beams is generated by a multilevel phase grating[9] from the single collimated beam of a high-power laser diode. The array of collimated beams is transmitted through an optical isolator, formed by a polarizing beamsplitter and a quarter wave plate, that serves as a two-way door for input and output. Then an objective lens creates an array of focused spots onto a SLM such as a symmetric self electro-optical effect device[10] (S-SEED) array. The modulated array of spots is reflected, collimated by the lens, reflected by the beamsplitter, manipulated by the interconnection hologram, and finally transferred to the next stage.

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The stop location of the objective lens is defined by the position of the phase grating where the array of collimated beams is generated. This implies that, in this staging scheme, a lens requirement is to have an external stop to permit the insertion of the beamsplitter and to cascade several stages without auxiliary pupil relaying optics. The fact that the angular position of the beams obeys the grating equation requires the objective to have an f-sin(θ) mapping so that the spacing of the focused spots is uniform as a function of the grating order. The SLM used in our application is an array of uniformly spaced S-SEEDs. These multiple quantum-well devices have a switching speed inversely proportional to their active window area so that to maximize the system's temporal speed it is crucial to minimize the window size, which in turn implies to minimize the focal length of the objective lens for a given lens aperture; this leads to a low f-number. Diffraction-limited performance on a flat surface and telecentricity in the image space are required.

No chromatic aberration correction is necessary since the wavelength stability required by the phase grating (850 nm $\pm$ 0.5) and narrow bandwidth (2 nm) required by the S-SEED array demand an essentially monochromatic light source. The field of view required to cover a square array of 4096 S-SEEDs spaced at 0.02 mm is square with a diagonal length of 1.81 mm. To obtain the necessary linear field of view there is a trade-off between the focal length of the lens and its angular field of view. Given the low f-number required and the desired overall system compactness, the focal length of the lens was chosen to be 15 mm. This led to an angular field of view of 7 deg, which is close to the limit of good performance that simple lens systems with the same requirements can provide. Table 1 summarizes the main lens requirements.

3 Lens Research

A search for an off-the-shelf lens that could meet most of the above requirements was conducted. Microscope objectives, laser collimating objectives, and scanning objectives

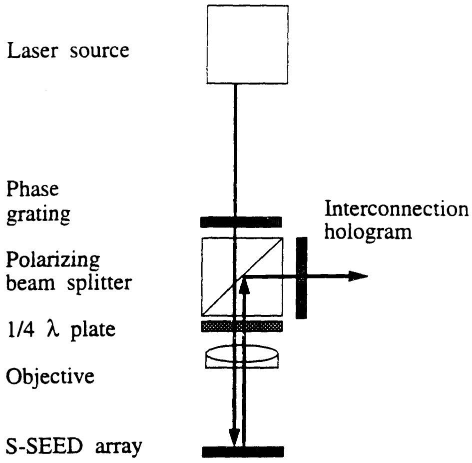

Fig. 1 A basic photonic switching stage.

were considered but none of them fulfilled all or even most of the requirements. Several (about 10) lens manufacturers were contacted and quotes for the lens design and the manufacture of 20 units were received with a price difference factor of approximately three. Given that an in-house lens design showed to be promising, it was decided to complete the design in-house and have the lenses made by a lens manufacturing company; the design is discussed below.

4 Lens Design

4.1 *General Considerations*

The lens requirements discussed above define, to a certain extent, the lens forms that can be used to solve the problem at hand. Experience indicated that a Petzval-type lens could be used as a starting design point. The Petzval portrait lens[11] consists of two spaced positive doublet lenses. The virtue of this lens configuration is that it can provide a high numerical aperture over a small field of view. The principle of operation of this lens, from a monochromatic design point of view, can be stated thus: two positive spaced lenses forming an objective allow the control of coma and astigmatism under a great diversity of conditions. This control is obtained using the relative lens powers, the lens shapes, and the lens spacing. Relevant characteristics of a Petzval-type lens are that its image aberrations can almost be independently controlled and that it has a great flexibility for locating the stop. This is in contrast to the Cooke triplet in which all the aberrations are closely dependent on each other.

In the original Petzval portrait lens, no provision exists to correct the Petzval field curvature; however, given the lens flexibility to control coma or astigmatism, the tangential field is flattened at the expense of introducing astigmatism. By adding complexity, there are many ways to correct spherical aberration, field curvature, and distortion in the two-element Petzval lens. The correction of one or more of these aberrations introduces additional coma or astigmatism, which can be controlled by the two positive lenses. The actual way spherical aberration, field curvature, and distortion are corrected dictates the final form of the Petzval-type lens. These general considerations summarize the experience gained during the lens design task and the next section illustrates how they were applied to solve the specific problem at hand.

Table 1 Lens requirements.

Focal length:	15 mm
Focal ratio:	1.5
Field of view:	7 degrees
Wavelength:	850 nm
Mapping:	F-sin(θ) ± 1.0 μm
Image surface:	Flat
Performance:	Strehl ratio > 0.95 over the full field
Telecentricity:	In the image space
Lenses:	Glass all spherical surfaces

4.2 *Particular Design*

The lens design that is the subject of this paper is illustrated in Fig. 2 and its specifications are given in Table 2. This lens evolved from a patented lens by Angenieux[12] but has no resemblance to the original Angenieux lens because two elements were eliminated and the stop was externally located. The lens operation relies on the use of a strong index break at the doublet[13] to control spherical aberration and on the use of a field flattener lens to correct field curvature and distortion. Coma and astigmatism are corrected by the relative lens powers, thicknesses, and spacing between the doublet and the positive lens. Distortion in this lens form can be controlled using the shape of the field flattener and was adjusted to provide the required f-sin(θ) mapping. The fine tuning of distortion can be accomplished during assembly by replacing the field flattener lens by another of similar construction but of different glass. The lens spacings are then slightly adjusted to restore optimum performance. Table 3 shows the variation of distortion and objective lens focal length as a function of glass type. The performance of the lens described in Table 2 is illustrated in Fig. 3 using wavefront plots for the 0.0, 0.7, and 1.0 field positions of a 4 deg semi-field of view. The wavefront plots indicate a well-corrected system because the peak wavefront deformation is approximately 1/10 of a wavelength and because a high Strehl ratio has been achieved without significantly sacrificing the depth of focus. The Strehl ratio over the entire field of view is greater than 0.95.

Figure 4 illustrates in a wavefront progression the cumulative deformation introduced in the wavefront as light propagates through the lens at the field positions 0.0 and 1.0. These plots were taken after each refraction with the reference sphere centered at the corresponding paraxial focal plane (except for the last one) and have different vertical scales in wavelength units at 850 nm. This graphical analysis is analogous to the familiar Seidel sums but displays the cumulative wavefront deformation in a more insightful form. The amount of wavefront deformation throughout the lens has a span of three orders of magnitude. It is observed that large amounts of aberration are generated at the cemented interface and at the flat surface. The field flattener lens introduces a significant amount of coma and astigmatism, which are corrected by the doublet and the plano-convex lenses.

The lens configuration involves only a flat surface, four different curvatures, and two equal thicknesses. These char-

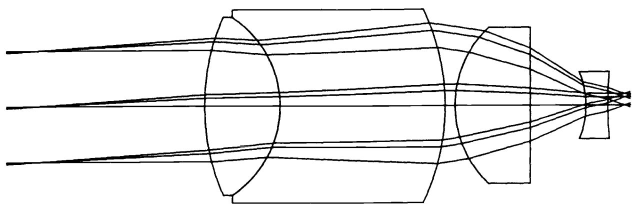

Fig. 2 Cross section of the objective lens.

Table 2 Lens specifications (in millimeters).

Surface	Radius	Thickness	Glass
1 (stop)		15.5	AIR
2	+21.086	6.835301	BK7
3	-10.090	15.03286	LASFN18
4	-21.086	0.90	AIR
5	+10.090	6.835301	BK7
6	flat	5.038552	AIR
7	-8.17	2.0	BAK4
8	+33.012	1.548716	AIR
9 (image)			

Table 3 Variation of distortion and focal length.

Glass of field flattener	Distortion (in micrometers at 4 degrees)	Focal Length (in millimeters)
SF2	2.3	15.9
SK2	2.4	15.7
BAK4 nominal f-sin(θ)	2.6	15.5
BK6	2.8	15.4
BK7	2.9	15.3
PK1	3.0	15.2

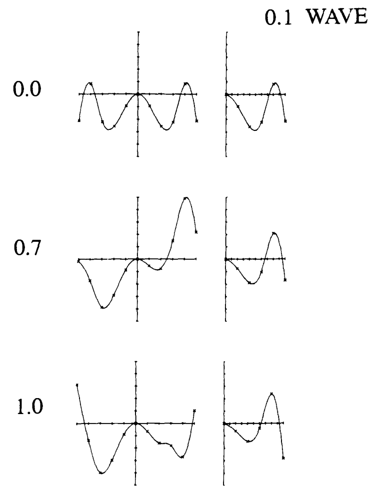

Fig. 3 Wavefront plots for the on-axis position and the 2.8- and 4-deg off-axis positions. The left column plots correspond to the tangential wavefront section and the right column plots to the sagittal section. The full vertical axis is 0.1 wavelengths, and the horizontal axis represents the full lens aperture at the exit pupil.

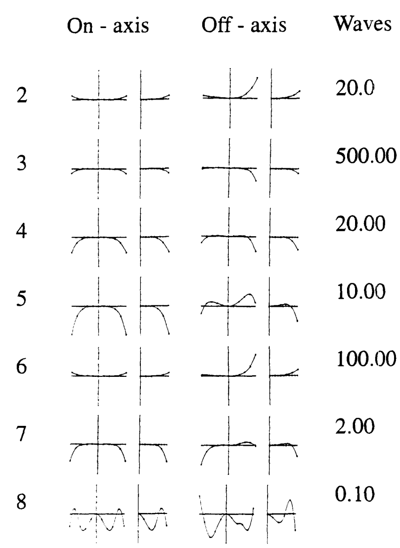

Fig. 4 Progression of the wavefront deformation throughout the lens for the on-axis (left plots) and 4-deg off-axis (right plots) positions. The numbers on the left indicate the lens surfaces and the numbers on the right indicate the full span in wavelength units of the vertical axis for each plot. The horizontal axis represents the full lens aperture at the exit pupil.

acteristics simplify the lens fabrication and could be designed because during the last optimization runs such parameters were not far from meeting such constraints. The doublet is made from BK7 and LASFN18 glasses to provide a high index break. The use of the exotic LASFN18 glass from SCHOTT was permitted because of its small lens size and its availability at the time of fabrication.[14] The objective lens solution is appealing because it is possible to meet the stringent requirements, simplify the lens fabrication, and still have a relatively simple configuration involving only four lenses. The objective back focal distance (working distance) is 1.5 mm, and the front focal distance (from the front focal point where the stop is located to the first lens vertex) is 15.5 mm. The front focal distance is as large as the objective front focal length of 15.54 mm. In the final lens design run, the surface curvatures were replaced by those of the nearest test plates from the manufacturer catalogue. Variation of the lens thicknesses and spacings were sufficient to restore the lens performance.

During the design process it was observed that the plano-convex lens could be placed in contact with the doublet lens. A lens contact can originate lens damage in shocking environments but can assure the exact axial positioning of a lens element. The tolerancing analysis showed that the objective performance is not critical with respect to the spacing of the doublet and the plano-convex lens and, therefore, they were air spaced. This permitted the use of the spacing to compensate manufacturing errors. In addition, mechanically it is easy to control lens spacings very precisely by the use of precision rings as spacers.

4.3 *Alternate Lens Forms*

The lens design presented previously was not the only lens form studied. Some other design forms that are of the Petzval type were analyzed. The only other lens found that consists of only four lenses and spherical surfaces and that provides similar performance to that of Fig. 3 is illustrated in Fig. 5 as form IV. This lens form has strong surface curvatures but provides a large back focal distance. This feature has resulted from the use of near concentric elements to control Petzval field curvature. The air lens between the third and fourth elements is critically adjusted to control distortion. The two front lenses of this alternate solution are equivalent in function to the doublet of the first lens discussed. These lenses introduce optical power and control spherical aberration. The two rear components are equivalent to the plano-convex and to the field-flattener lens. These lens pairs add optical power and correct field curvature and distortion. The objectives shown as forms I and IV can be divided into two main components that can be interchanged to derive four different objectives forms as shown in Fig. 5. For our application, form I is the best from the point of view of image quality and manufacturability; form III has been considered in the design of laser scan lenses.[15,16] Manufacturing advantages of form I are the use of a doublet to simplify the lens barrel by effectively decreasing by one the number of elements to be mounted; the matched surface radii and thicknesses that simplify lens fabrication; the flat surface of the third element that simplifies the lens barrel and alignment; and, except for one surface of the field flattener, the relatively long radii of all the surfaces, which ease the grinding and polishing operations.

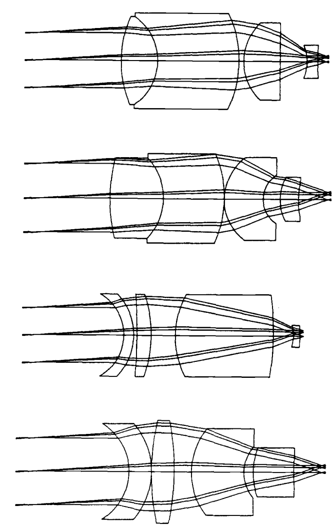

Fig. 5 Lens forms comprised of two parts: the two front lenses of each form compose the first part that contributes optical power and corrects spherical aberration. The two rear lenses compose the second part that corrects Petzval field curvature and distortion. The front and rear parts of lenses I and IV are interchanged to create forms II and III.

5 Lens Tolerancing

The tolerancing of the lens was an important task since the lens cost and performance depended on it. The search-and-design task involved approximately four weeks of work (160 design h) and the tolerancing study required a similar amount of time. Much effort was dedicated to achieve a high degree of confidence that the lens would work after specifying a set of tolerances. This required understanding in detail the behavior of the lens with perturbation. The tolerancing was performed manually and was approached by dividing the task into axial and tilt tolerancings.

The axial tolerancing involved changes in all the parameters that maintain the axial symmetry of the lens. These are the radii of curvature, thicknesses, indices of refraction, and spacings. Departures of these parameters from nominal values introduce mainly spherical aberration and linear coma. The tilt tolerancing involved changes that alter the axial symmetry of the lens, specifically surface tilts. These changes introduce mainly uniform coma and astigmatism, linear astigmatism, and field tilt. Surface decenters were treated as surface tilts and thickness changes. Furthermore, during the tilt tolerancing, the objective was treated as a plane symmetric system because the lenses can be rotated to be aligned and create such symmetry. Lens wedges in the doublet, the plano-convex lens, and the field-flattener lens can be oriented to form eight possible lens combinations that have plane symmetry. In some of these combinations, the effects caused by the lens wedges add; in others, they cancel.

In performing the tolerancing analysis, the decentering and spacing of the third and fourth elements were used as compensators to restore the lens performance and increase the magnitudes of the tolerances. Only lens decenterings were allowed because mechanically they are simpler to implement compared to lens tilts. This implied that in assembling the lens a final adjustment had to be performed to meet the lens imaging requirements. It was observed that if lens tilts were also allowed to restore performance, then even larger surface tilts of other components could be permitted. Without compensators, the objective would have required tolerances that are one order of magnitude smaller to guarantee the lens performance, and the manufacturing cost would have increased considerably. Table 4 gives the axial and tilt tolerances assuming the use of compensators.

The lens mounting must provide some means to adjust the two lens spacings and to center the last two lenses. The range of adjustment necessary for the first spacing is ± 0.8 mm from the nominal value, and for the second spacing it is ± 0.1 mm. The performance of the lens was found to be very sensitive to the second spacing, which must be adjusted and maintained to about 0.01 mm. The maximum-compensating decenter needed for the last two elements is 0.2 mm. The tolerances were set to have a worst case (no cancellation of errors) Strehl ratio performance of 0.85 over the entire field of view. This figure does not include the surface figure errors or the errors from glass inhomogeneities. The surface figure tolerance as specified is at the threshold of becoming a tight requirement. It was decided to have 30 lens sets made and to allow the possibility of having some few objectives out of specification (all the errors adding up) and the rest performing as needed. This philosophy is ap-

Table 4 Lens tolerances.

1) Diameters:	+ 0.0 ; - 0.1 mm.
2) Thicknesses:	+ 0.05 ; - 0.05 mm.
3) Radii:	Fit to test plate ± 3 fringes.
4) Figure:	Less than 1/3 of a fringe at 546 nm (mercury green); fringes must be smooth.
5) Lens wedge:	Less than 5 arc-minutes for BK7 and BAK4 lenses; less than 2.5 arc-minutes for LASFN18 lens.
6) Glass homogeneity:	$\pm\ 1X10^{-6}$

propriate given that specifying a tight tolerance in the figure can result in doubling the component price.[17] The asymmetric distortion that results from tilts and decenterings in the analysis of the worst case lens is about 1 μm at the edge of the field and the image plane tilt is about 15 arcmin; these image defects were deemed tolerable. The small changes in the lens's first-order properties such as the focal length were at first of no relevant concern because pupil relaying optics were planned to be included and could be used to compensate for magnification errors. However, as the switching system was modified from the original design, the requirements of having an external stop to overcome the use of pupil relaying optics and the matching of the focal length of at least 6 lenses to within 0.1% became important.

Two other aspects of the tolerancing were the doublet cementing and the lens performance as a function of the wavelength. The layer of cement between the first two lenses was modeled for different thicknesses (0 to 0.05 mm) and indices of refraction (1.51 to 1.85). The result was that the lens performance is not altered or it can be restored using the compensators. Performance restoration can also be accomplished for small changes in the nominal wavelength of at least 10 nm.

6 Lens Ordering

The objective lens designed (form I) was approved for fabrication because it met the imaging requirements, it was simple and manufacturable, and because no other lens of about 15 studied could match its overall performance. Lens drawings were generated and sent to three lens manufacturing houses for quotation. The quote amounts for the manufacturing of 30 objectives (120 lenses) with a turnaround of a 3- to 4-month period varied by a factor of 5.

In ordering the lenses, the advice given[18] in regard to the advisability of having a good communication with the manufacturer was well taken and no incorrect parts were received. The shipment of the last set of lenses had a delay of about three months; this was due in part to some unforeseen experiments that had to be performed to test the lens transmission and to test the strength of the cement on the antireflection coating in the doublet interface. The lens surfaces were specified to be antireflection coated to provide a transmission of 99.75% per lens surface. Coating one of the cemented surfaces of the doublet was necessary because of the strong index break between the BK7 ($n = 1.51$) and the LASFN18 ($n = 1.89$) glasses. The convex surface of the interface was left uncoated and the concave one was coated with a 0.27-waves (850-nm) layer of MgO ($n = 1.71$) to reduce the interface reflectivity to less than 0.15%. The reflectance of the interface was computer modeled, with consideration for the angular incidence spread of light, the index of the layer of cement, and its specified thickness range (10 to 25 μm).

When we ordered the lens components there was no information available[19] about the adherence properties of cemented and coated interfaces; therefore, it was necessary to test the adherence of the cement to the MgO coating. For this, two doublets, one with the MgO coating and another without the coating, were requested and tested. The coated doublet objective passed simple adherence and shocking tests such as statically holding 10 times its weight when the load was supported only by the BK7 lens and tapping it with a pencil. The measured light transmission for the doublet with the uncoated interface was 99%, and for the coated was 99.5%. The balance of the 28 doublets were specified to be fully coated because light loss in our photonic switching system is of great concern.

7 Lens Barrel

While the lenses were manufactured, two lens barrels were designed and made in one of our instrument shop facilities. One barrel had screws to adjust the lateral position of the plano-convex and the field-flattener lenses. The other barrel had no radial adjustments for those lenses and its inner diameters closely matched the lens diameters. In communicating with the manufacturer it became clear that their lens-making practices could attain easily a surface tilt of no more than 2 arcmin without increasing the lens cost. The manufacturer decreased the lens diameter tolerances to half of those requested. Since the tolerances specified were for a worst case it was deemed appropriate to make the second lens barrel to try to assemble the lenses with no lateral adjustments. When two complete sets of lenses were available they were assembled in the barrels and adjusted to perform as expected. The presence of the adjusting screws, the inferior lens mounting at three questionable radial points, the radial screws alignment sensitivity, and the success of the simpler barrel with no screws made us discard the use of barrels with adjustment screws.

The lens housing illustrated in Fig. 6 consists of five parts: the barrel, two ring spacers, a plastic washer, and a threaded retaining ring. The lens barrel and the spacer rings are made from stainless steel stock. The first spacer has bevels on both inner edges to contribute to the lens alignment and to provide mechanical interfaces to the tangentially contacting convex surfaces. To simplify the lens alignment and the second lens spacer, the field-flattener lens was specified to be oversized and have flat annular surfaces. The second spacer has flat sides to rest on the flat surface of the plano-convex lens and on the flat annulus of the field flattener lens. The inner diameters of the barrel were specified with a $-0.0+0.025$ mm tolerance, and some sets of spacers with different thicknesses were ordered to adjust the critical spacing between the plano-convex lens and the field flattener. The typical wedge in these spacers is of the order of 1 arcmin. To avoid the loss of working distance, a mounting recess was designed on the field-flattener lens edge. The plastic washer and the brass retaining ring hold all the components in position and complete the lens housing.

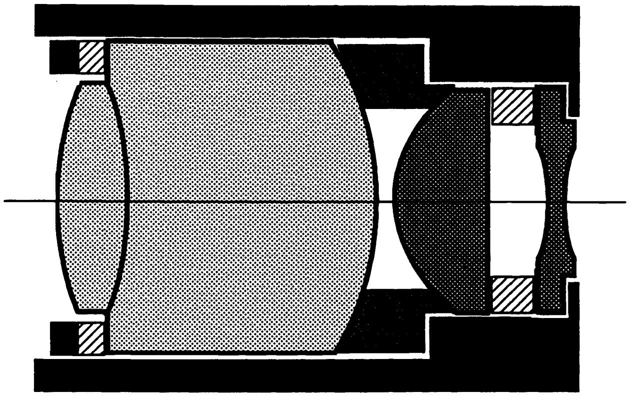

Fig. 6 Cross section of the lens barrel and the lenses.

Table 5 Objective performance.

Strehl ratio (at the worst field position)	Number of objectives
0.95	4
0.90	10
0.85	4
0.80	3
0.75	3
Lower than 0.75	3

8 Lens Assembly and Testing

The objective assembly was performed on a clean air station by means of simple techniques to clean and to vacuum handle the lenses. A Twyman-Green interferometer with a diode laser source at 850 nm was arranged to interferometrically test the objectives. A rotary stage was used to hold the lens and allow the lens to be tested on-axis and off-axis. An iris was located at the proper distance to create the lens stop and a concave spherical mirror was used to reflect back the light focused by the objective to obtain a double-pass test configuration. Essential in the assembly and testing was the ease with which the lens could be assembled, disassembled, and tested; much effort was dedicated to make these tasks as easy as possible. The interference fringes were imaged onto a CCD camera, viewed on a TV screen, and analyzed with FAST! V/AI fringe analysis software, Phase Shift Technology, Tucson, Arizona.

Once the lenses of an objective were assembled in a barrel the objective was tested on-axis. If any spherical aberration was detected it was corrected by adjusting the thickness of the second lens spacer. Then the uniform (on-axis) coma was evaluated and corrected by rotating the doublet lens, the field-flattener lens, or by exchanging any of these lenses. Spherical aberration and uniform coma were the aberrations most frequently corrected. The correction of uniform coma sometimes was tedious. After the on-axis correction was performed, the off-axis field performance was tested. Four field positions at 3.5 deg off-axis and at 0, 90, 180, and 270 deg around the field were evaluated. Any amount of linear coma observed was corrected by adjusting the thickness of the first spacer. Uniform astigmatism and linear astigmatism rarely were observed and when they were significant another lens combination was tried.

The first objectives assembled were relatively easy to adjust and the last ones were difficult and required more time. It is estimated that an average of 2 h was required to assemble each of the 27 objectives completed. The objectives were characterized using as a figure of merit the Strehl ratio of the worst field position of the five mentioned above. The Strehl ratio was calculated with FAST! and Table 5 gives the number of objectives that provided at least the indicated Strehl ratio. It is appropriate to mention that the good performance achieved with the use of barrels with no lens centering screws is due to the better lens centering by the manufacturing house and to the lens assembly technique used. The lens-centering (edging and mounting) level is reflected in the measured angular difference between the barrel mechanical axis and the lens optical axis. This difference in the average for 9 lenses measured is 3.2 arcmin. Except for the manufacturer improved tolerances in the diameter and lens wedge, Table 4 still represents the lens tolerances given to the manufacturer.

To measure the focal length and its distribution, an array of beams created by a diffraction grating of known period was focused onto a graticule. This graticule served to measure the spot position as imaged by another objective on a TV system. By knowing the grating period, the spot spacing, and the wavelength of illumination, we found the focal lengths. From the 27 objectives completed, 6 were found with a variation of less than 0.1% in their focal length. Computer modeling of the objectives showed that distortion is insensitive to manufacturing errors of the order of magnitude specified; the negligible variation of this aberration was not a concern. With a collimated beam of 5 mm in diameter the light transmission in the assembled objectives was measured to be approximately 96% across the field of view. The lenses and barrel components are illustrated in Fig. 7 and a completed objective is shown in Fig. 8.

9 Conclusion

In this paper we have presented design, assembly, and testing details of an objective lens used in a free-space photonic switching system. The completion of 27 objectives, including design, manufacturing, assembly, and testing, took approximately 1 yr. The lens design analysis and the successful fabrication of the lens indicated that we arrived at a good lens design form. Essential to the success was the tolerancing analysis and the communication established with the manufacturer and, during the lens assembly, was the easy, quick, and user-friendly test setup. We presented several details about the manufacturing of a lens because they are rarely discussed in the literature.

Even though the design and manufacturing of lenses is considered a mature technology, the wide difference in quotes obtained for the manufacturing of complete objectives or individual lenses suggested to us that the lens industry has not reached maturity in pricing the manufacture of small quantities of specialized lenses. When a given lens cannot be found as an off-the-shelf item, it is not clear which is the

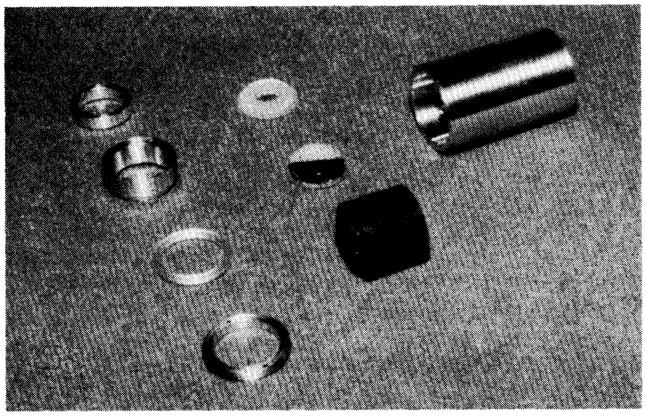

Fig. 7 The lenses and barrel components.

Fig. 8 A fully assembled objective.

best route to follow to successfully obtain an objective at a competitive cost.

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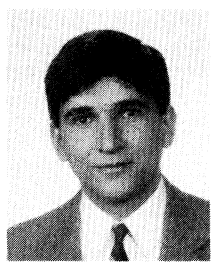

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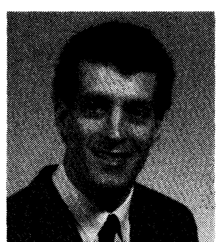
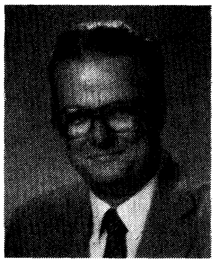
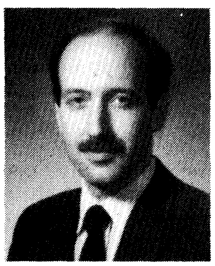


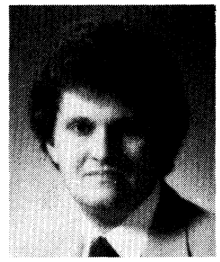
Frederick B. (Rick) McCormick, Jr., received a BSEE from the University of Washington, an MSEE from the Georgia Institute of Technology, and a PhD from the Heriot-Watt University (Edinburgh). After joining AT&T Bell Laboratories in Naperville, Illinois, he worked on the @5ESS sup TM@ electronic switching system. Presently, he is designing and building free-space optical interconnection systems in the Photonic Switching Department there. Since joining the Photonic Switching Department in 1985 he has worked on holographic and conventional free-space optical interconnections for photonic switching and optical computing. He has also investigated the application of nonlinear Fabry-Pérot etalons and symmetric self electro-optic effect devices in photonic switching systems. His recent research interests include optical system design and packaging for free-space optical systems using FET-SEED "smart pixel" processing arrays. He holds seven patents and has published over 70 journal and conference papers and three book chapters. McCormick is a member of Tau Beta Pi, OSA, and SPIE.



Robert Webb received his MS degree from New York University in 1966 and his BS degree from Queens College in 1960, both in physics. Since 1962 he has designed and built high-power laser processing systems, developed both glass and crystalline optical components, and worked on manufacturing issues for implementation of industrial laser systems. He has been a member of the technical staff at the AT&T Engineering Research Center in Princeton, New Jersey, since 1977, where he is currently involved in precision optical assembly of both fiber and free-space optical interconnects. Webb is also an adjunct professor of physics at Stevens Institute of Technology and is a member of SPIE and the OSA.



Randall J. Crisci began his career at Western Electric's Engineering Research Center in 1980 as an engineering associate working in the Laser Studies Group on telecommunication-component laser material processing. His work there was in the areas of laser alloying, surface melting, planarization, barcode generation, thin film resistor trimming, HIC bonding, and laser microvia drilling. In addition, Crisci coauthored AT&T's Corporate Laser Safety Standard. He is currently a member of the technical staff in the Photonics Manufacturing Technology Department at AT&T Engineering Research Center in Princeton, New Jersey. His recent work has been in tunable fiber Fabry-Pérot filters, wavelength division demultiplexers, polarization demultiplexers, 2-D fiber arrays, free-space optics, multielement lens assembly, and lens interferometry. Crisci received a BSEE degree, summa cum laude, from Drexel University, Philadelphia, Pennsylvania, and an associate degree in laser electro-optics technology from Camden County College, New Jersey. He is currently working on a MS degree in engineering at Rensselaer Polytechnic Institute, Troy, New York.



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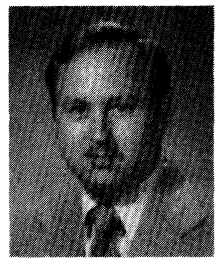

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