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Developments in holographic-based scanner designs

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ABSTRACT

Holographic-based scanning systems have been used for years in the high resolution prepress markets where monochromatic lasers are generally utilized. However, until recently, due to the dispersive properties of holographic optical elements (HOEs), along with the high cost associated with recording "master" HOEs, holographic scanners have not been able to penetrate major scanning markets such as the laser printer and digital copier markets, low to mid-range imagesetter markets, and the non-contact inspection scanner market. Each of these markets has developed cost effective laser diode based solutions using conventional scanning approaches such as polygon/f-theta lens combinations. In order to penetrate these markets, holographic-based systems must exhibit low cost and immunity to wavelength shifts associated with laser diodes.

This paper describes recent developments in the design of holographic scanners in which multiple HOEs, each possessing optical power, are used in conjunction with one curved mirror to passively correct focal plane position errors and spot size changes caused by the wavelength instability of laser diodes. This paper also describes recent advancements in low cost production of high quality HOEs and curved mirrors. Together these developments allow holographic scanners to be economically competitive alternatives to conventional devices in every segment of the laser scanning industry.

Keywords: holographic scanner, scanning, imagesetter, holographic optical element (HOE), optical replication, achromatization, diffraction grating, cold-forming, injection molding

1. INTRODUCTION

Starting in 1982, holographic deflectors, mounted to a scan motor and coupled with an f-theta lens assembly, have made significant in-roads into the laser output scanning market[1]. These systems consist, in essence, of a polygon/f-theta lens or pentaprism/f-theta lens scanner with the polygon or pentaprism replaced by a holographic deflector. The deflector consists of multiple plane diffraction grating facets in a photo-emulsion on a glass substrate (see Figure 1).

The attractive features of these holographic deflectors have been widely described in literature written by Beiser[2] and Kramer[3] as well as others. Compared to mirror-based deflectors, the major attributes include:

1. Reduced sensitivity to motor shaft wobble by a factor of >1000 when the holographic deflector operates in the Bragg regime where the nominal input and diffracted angles are equal (see Figure 2). This feature allows the optical design to be simplified significantly;

2. Reduced scanner windage due to the aerodynamic nature of the scan disc. This feature allows higher scan rates;

3. Reduced sensitivity to motor scan jitter due to the transmissive nature of the deflector. This feature allows the use of a ball-bearing motor in place of an air-bearing motor.

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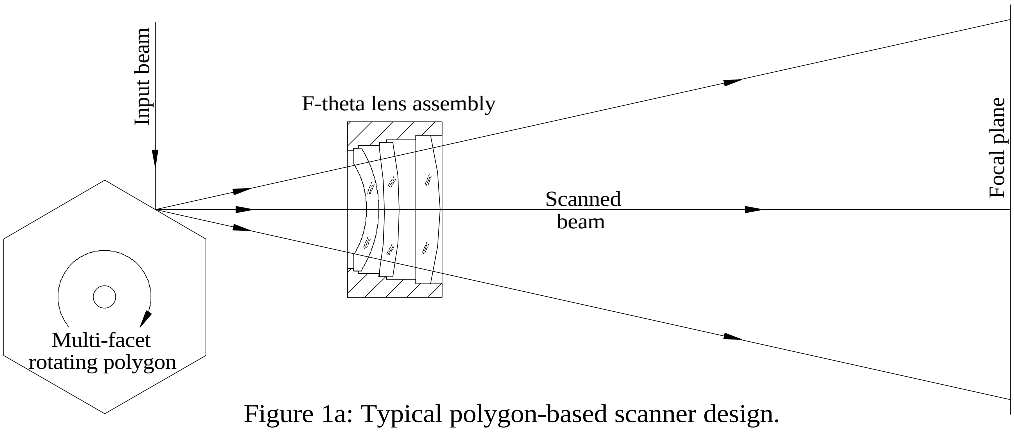


Figure 1a: Typical polygon-based scanner design.

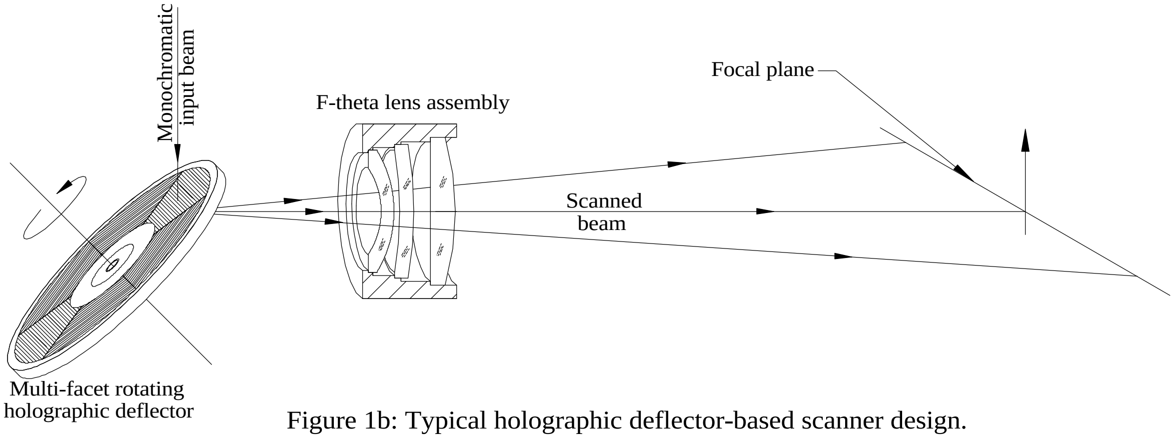


Figure 1b: Typical holographic deflector-based scanner design.

These benefits afford holographic deflectors a considerable price/performance advantage over polygon or pentaprism based designs. However, since HOEs are dispersive in nature, scanners consisting of a single HOE (in this case the holographic deflector) are limited to monochromatic laser-based devices.

During the 1980s, a transition from monochromatic lasers to diode lasers took place in the low resolution (300 dpi) laser printer industry. As the output quality and the lifetime of these lasers have improved, they have been increasingly integrated into higher resolution devices. By the early 1990's, laser diodes could be found in systems ranging in resolution from 300 dpi to 4000 dpi. Today, though laser diodes are not found in every scanning system, they have become increasingly popular due to their cost per milliwatt advantage over gas and solid state lasers and their ability to be intensity modulated at rates of 100 MHz and higher.

Laser diodes used in most scanners today are index guided. These lasers generally exhibit single mode operation at a given temperature. However when the laser is modulated, the temperature of the laser resonator fluctuates, causing its refractive index to change. This in turn causes the wavelength to shift or "mode hop." It has been shown empirically that wavelength shifts of up to ± 1 nanometer can be expected during the writing of a single scan line of random output data.

Since HOEs are highly dispersive elements, wavelength changes of 0.01 nanometer or less can cause detrimental effects at the focal plane. Therefore, the proliferation of laser diode-based scanners has confined these holographic deflector-based systems (see Figure 1b) to the ever-shrinking market for monochromatic high resolution scanners.

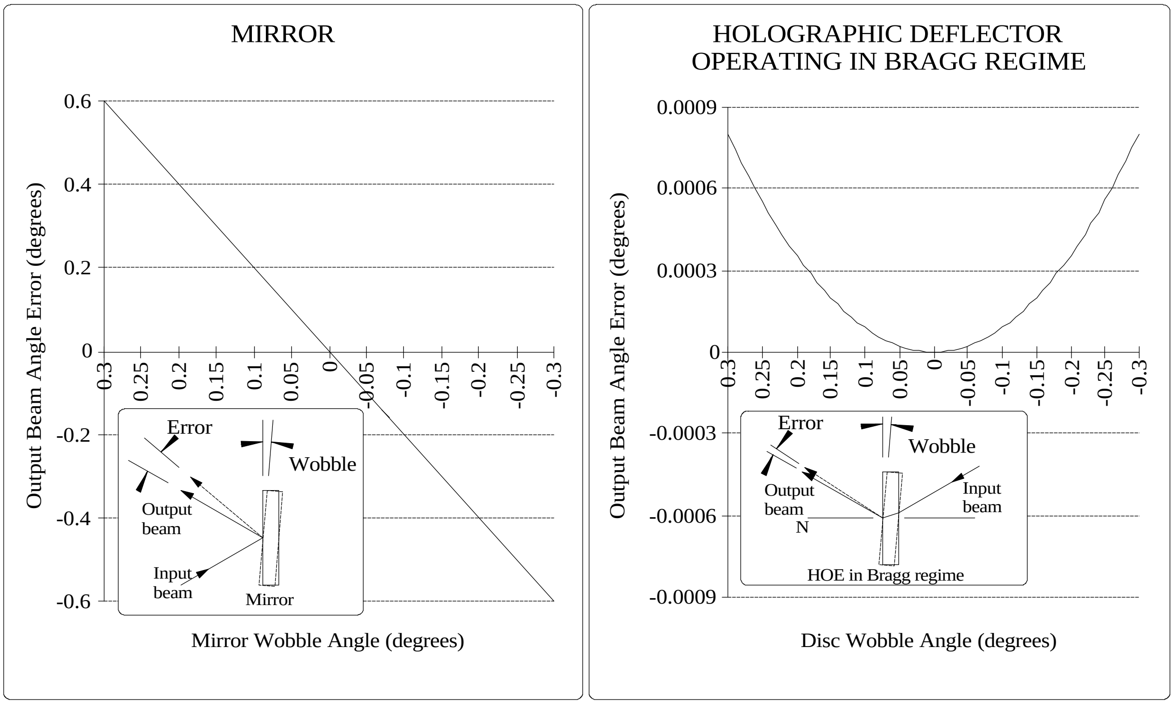


Figure 2: Comparison of output beam angle error due to motor wobble.
Note 1500:1 reduction in wobble error for HOE deflector.

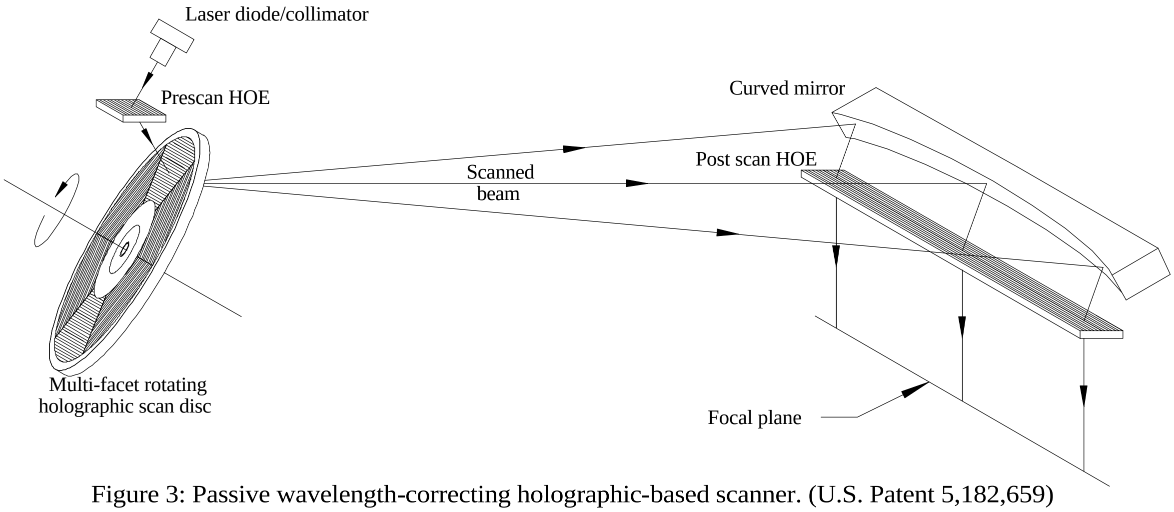


Figure 3: Passive wavelength-correcting holographic-based scanner. (U.S. Patent 5,182,659)

2. HOLOGRAPHIC SCANNERS OVERCOME WAVELENGTH SENSITIVITY

In the early 1990s, Holographix, Inc. devised and patented a way to passively correct laser diode wavelength shifts in holographic-based scanners[4]. The passive correction is accomplished by eliminating the f-theta lens assembly and replacing it with a "prescan" HOE positioned before the holographic scan disc (deflector), a curved mirror after the scan disc, and a "postscan" HOE between the curved mirror and the focal plane (see Figure 3). To compensate for the removal of the f-theta lens, optical power is designed into each HOE. Using multiple HOEs and a curved mirror, a high resolution laser scanner can be designed exhibiting a 1000:1 reduction of wavelength induced beam placement errors at the focal plane (see Figure 4).

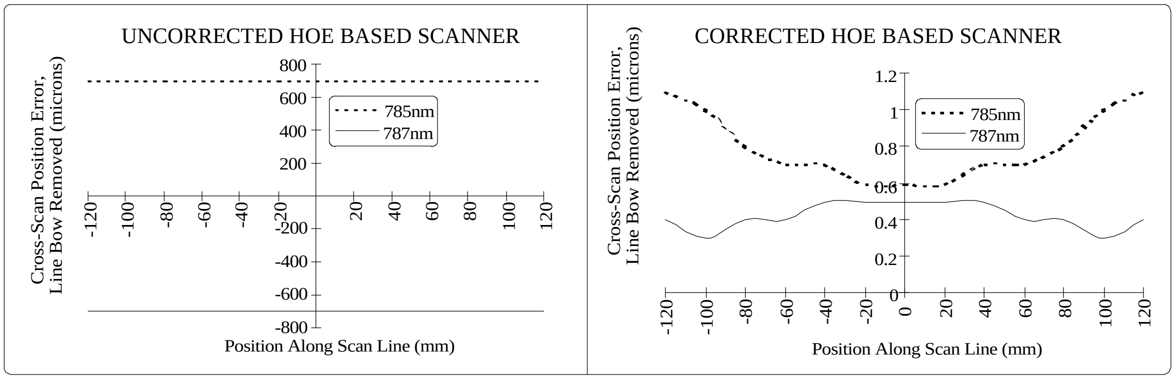


Figure 4a: Uncorrected and corrected cross-scan beam position error along focal plane due to wavelength shifts. Note scale of corrected plot on right is 1000X smaller than scale of uncorrected plot on left.

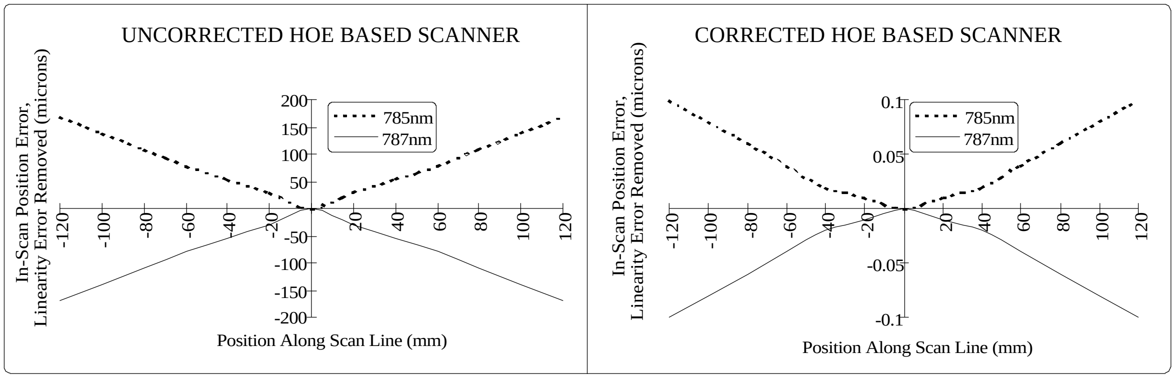


Figure 4b: Uncorrected and corrected in-scan beam position error along focal plane due to wavelength shifts. Note scale of corrected plot on right is 2000X smaller than scale of uncorrected plot on left.

Over the last six years, Holographix has worked with Optical Research Associates and their CODE V® optical design software to refine and customize this basic concept to develop scanners that meet customer requirements ranging from 300 dpi laser printers to 4000 dpi high resolution imagesetters. During this period, a number of design improvements have been made with the focus on driving down costs by reducing components while maintaining the system parameters necessary to meet continually tighter industry specifications. This has been accomplished by adding more complex optical power to the scan disc and the postscan HOE, allowing the prescan HOE to be deleted from some designs.

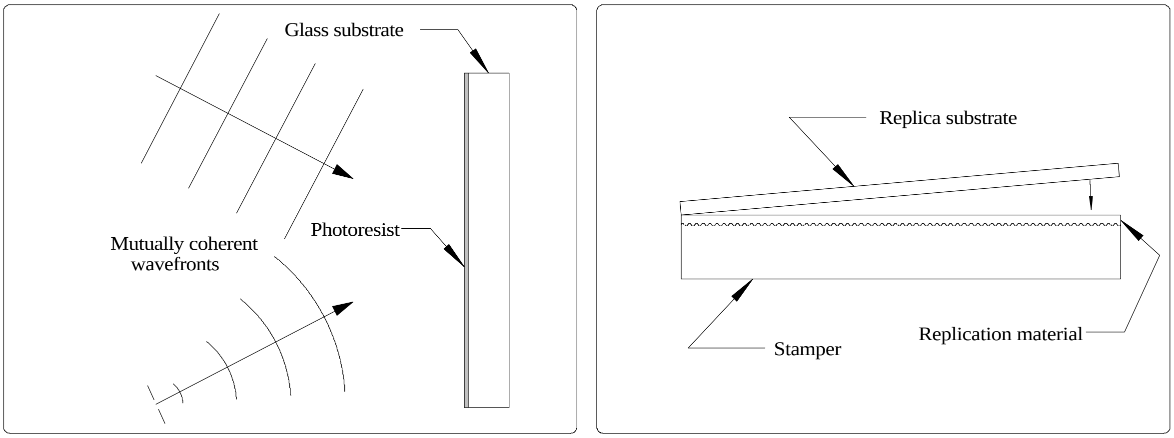
While adding more complex optical power to the HOEs may sound like it has significant cost consequences, it should be noted that unlike in conventional scanners, the cost of adding complex optical power is non-recurring in the form of tooling. That is to say that since the optical power is formed on the HOE during recording, the complex recording lens (i.e. the tooling) must be fabricated only once. In contrast, as conventional scanners become more complex, the complexity is reflected in higher component costs of each system.

3. LOWERING THE COST OF HOLOGRAPHIC SCANNERS

3.1 Replication of holographic optical elements:

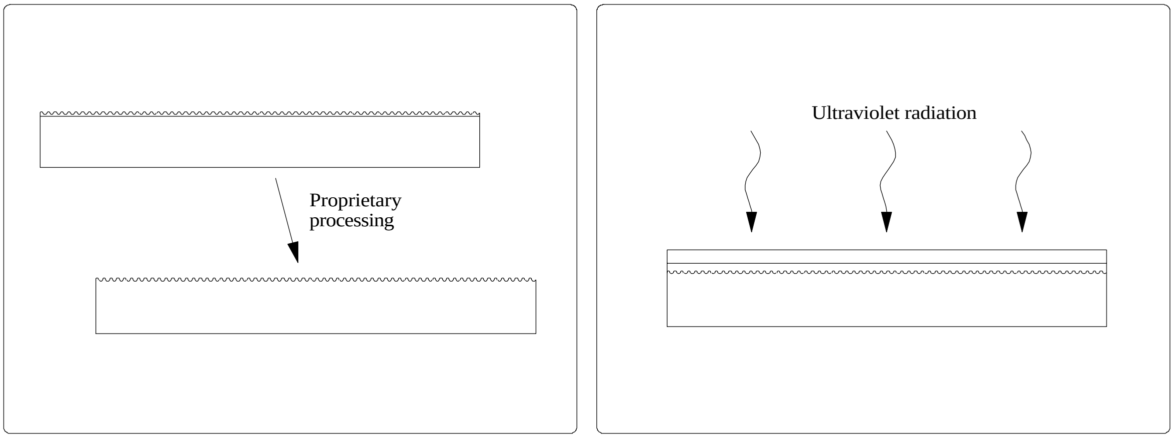
In the past, a major handicap for holographic-based systems has been the high cost associated with recording each "master" HOE. This process is labor intensive, requiring numerous intricate steps to complete one HOE. Thus, it is difficult to drive the cost down appreciably even at higher volumes.

Recognizing that the HOE was a major system cost driver, Holographix embarked in the early 1990s to develop and patent a replication process for manufacturing high quality, low cost HOEs[5]. Holographix has refined this process over the last several years, enabling the production of a wide range of HOEs including low cost injection molded replicated HOEs for the



STEP 1: Master recording

STEP 3: Application of replication material and substrate



STEP 2: Conversion of master to stamper

STEP 4: Ultraviolet curing of replication material

Figure 5: Typical process steps for replicating HOE's using ultraviolet cured replication material

low resolution laser printer market as well as high quality “cold-formed” replicated HOEs for the high resolution imagesetting and non-contact inspection scanner markets.

For the low resolution (300 to 600 dpi) laser printer market, Holographix has developed an injection molding process to meet the market’s high volume production (>20K units/year) and quality requirements. Due to the intricate grating structure of the HOE, the conventional molding process had to be modified. Therefore, during process development, careful consideration was given to the thermal requirements of the mold to allow the plastic to flow into the groove structures prior to solidifying. Producing HOEs in this manner allows them to be fabricated for significantly less than $1. each in high volume due to the rapid (<10 second) cycle time.

For the higher resolution (800 to 4000 dpi), lower volume (<5K units/year) imagesetter/scanner markets, Holographix has developed a cold-form replication technology to form the grating structure on a high quality substrate (glass, aluminum etc.). The process involves first creating a master HOE, then from the master, a stamper is created consisting of the negative of the information that is to be transferred into the replication medium. Liquid ultraviolet light curable replication material is then applied to the stamper and sandwiched between it and the replica substrate on to which the replica is to be transferred. The assembly is then placed under a ultraviolet light source, using a conveyor system, for 1 to 5 seconds depending on material thickness. At this point, the replication material has cured with the information from the stamper transferred into it and the material is preferentially adhering to the replication substrate. The final step (not shown) is to separate the replica from the stamper (see Figure 5).

This replication process provides the capability to produce thousands of identical high quality HOEs from one master. This not only reduces the cost of the HOE significantly, but it also provides the repeatability necessary for the production of high quality scanning systems. In 1995, Holographix shipped its first replicated scan discs to a customer licensing our technology. Since then, hundreds of high quality replicated HOEs have been sold to customers utilizing Holographix' designs.

For the mid-resolution (600 to 800 dpi), mid-volume (5K to 20K units/year) laser printer market, the two processes of injection molding and cold-forming can be combined. The hybrid process involves first using conventional injection molding to make the plastic substrate. The grating structure is then formed on the substrate using the cold-form replication process. This combination provides the benefits of low cost associated with injection molding along with the high quality of cold-forming.

3.2 Elimination of f-theta lens assembly:

The f-theta lens assembly is often the most expensive component in the scanning system. A number of systems consisting of a holographic scan disc possessing optical power and a curved mirror have been developed at Holographix that effectively eliminate the multi-element f-theta lens assembly (see Figures 3 and 6). The curved mirror in the holographic-based system serves many functions including line bow correction, field flattening, and linearity correction. It also serves to make the scan telecentric, which is a critical system attribute in non-contact measurement devices as well as input scanners.

Since the curved mirror consists of only one optical surface compared to four or more surfaces for a typical f-theta lens assembly, there is a tremendous opportunity to reduce cost. However, since the surface of the mirror is often aspheric or cylindrical, conventional polishing procedures are not usually applicable. Therefore, low cost methods of producing the curved mirror had to be identified to make this scanner design feasible. Holographix has identified a number of approaches to fabricating curved mirrors and has developed production processes for each approach. Each process addresses the particular cost and quality requirements of each segment of the scanning market.

For the low resolution, high volume laser printer market, a gas-assist/compression injection molding process has been developed to form the mirror in plastic[6]. The gas-assist step is used to form a stiff, light-weight structure by evacuating the core plastic before it solidifies in the mold. The compression step is then used to form the mirror surface into the plastic. Since the cycle time to make one part is approximately 45 seconds, curved mirrors can be produced in volume in the $1-2 range.

For the mid-resolution, mid-volume laser printer market, both injection molding and cold-forming are used to form the mirror. The hybrid process involves first injection molding the curved blank substrate using conventional processing. The mirror surface is then formed on the substrate using the cold-form replication process.

For the low to mid-resolution (800 to 2000 dpi), lower volume (500 to 5K units/year) imagesetter/scanner market, the optical surface of the curved mirror is formed by diamond turning an aluminum substrate. Newly developed diamond turning machines capable of 5 nm resolution have allowed this fabrication technique to become a viable method for the production of high quality mirrors. Diamond turned curved mirrors have been proven suitable for systems with resolutions of up to 2500 dpi.

For the high resolution (>2000 dpi), low volume (<500 units/year) imagesetter/scanner market, replication technology is employed to apply a high quality optical surface onto the diamond turned mirror blank using a conventionally polished optical mold. Replication in this case is used to remove the diamond turning marks which diffract light creating optical noise at the focal plane.

3.3 Low cost monochromatic systems:

By introducing replicated holographic scan discs and low cost curved mirrors while eliminating the f-theta lens assembly, the cost of monochromatic holographic-based scanners can be significantly reduced. Since the holographic-based scanner design in this case does not require wavelength correction, the prescan and postscan HOEs can be eliminated, simplifying the design considerably (see Figure 6). A 2500 dpi resolution computer-to-plate imagesetting device based on this design is being manufactured at Holographix for a major prepress systems manufacturer. The design employs both replicated scan discs along with diamond turned curved mirrors.

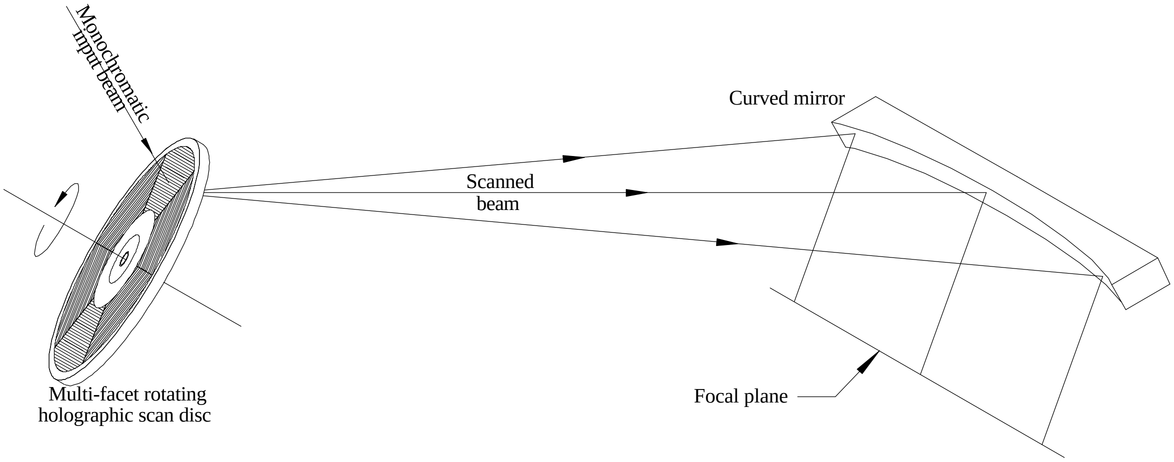


Figure 6: Holographic-based scanner for monochromatic laser source.

4. CONCLUSIONS

Recent developments in the design of holographic-based scanners now allow holographic systems to compete with more traditional approaches in every segment of the laser printer, imagesetter, and inspection scanner markets as well as other markets requiring a laser scanning device. These developments include passive correction of wavelength shifts which allow the use of laser diodes, the development of low cost replication techniques to reduce the cost of the HOEs, and the replacement of the f-theta lens with a low cost curved mirror, reducing the overall cost of the scanner. Both laser diode and monochromatic laser based holographic scanner designs are now in production confirming that these designs provide cost effective alternatives to conventional scanners.

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