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SBIR PHASE II FINAL REPORT

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FINAL REPORT, August 1990
project SBIR II DAA - 87 - C - F022

SUMMARY OF ACTIVITIES

We began our phase II work by upgrading our facilities. By the end of July 1988 we had improved two buildings, added an etalon to an AL 909 Argon laser and constructed apparatus for exposing spatially multiplexed devices. We added two new electronic air filters and built a large class 100 clean hood for coating substrates up to 24 inches in diameter. We had by then already supplied the first of many batches of low spatial frequency gratings recorded in dichromated gelatin (DCG). Many attempts were made to make notch filters in dupont photopolymer and a 3 month study of a new photopolymer developed at USU was funded and completed. The work on the photopolymers resulted in a process patent and a new class of fluorescent material. Steve Bialkowski finished a program that modeled non uniform holographic mirrors prior to beginning this work.

In August we hired Scott Schicker, a chemist from Dupont who is still with us at the end of the contract. We made up more low spatial frequency gratings and got Steve Bialkowski doing research on fiber optic assemblies. We also started to make a display hologram of a laser range finder but lost an Argon tube so we switched to a red He Ne to do red film studies and lost that laser also. By the end of the year we had finished insulating our buildings and had an operating Argon laser and lost a tube again. *We had made the range finder copies in at least two formats,* delivered some slanted gratings, completed a fiber hardware review and discovered that aluminum can have inclusions that will react violently with trichloroethane. We made more transmission gratings but had trouble getting enough modulation in 2 degree gratings.

By the end of the first quarter of 1989 we had produced an efficient 1.06 micron collimation lens but the off axis aberrations were excessive, especially the astigmatism, and its usefulness was limited. We were able to make first order corrections for spherical aberration only and had no way to quantify all the errors due to wavelength change. We also made copies of a multiplexed master of satellite scans of the earth but they suffered from distortion and small angle of viewability. The distortion was again due to a wavelength change but the viewing angle was limited by the choice of master format. We fixed Scott up with a 386 based machine and we made a lot more transmission gratings and practiced color control in DCG plates.

The second quarter saw yet another double laser breakdown, we lost about 45 days due to a small inclusion in the bore of a new argon tube. We still managed to get out a lot of small gratings in the 40 and 80 line range more copies of the satellite map plus DCG copies of the ERIM Beam Former CGH. The ERIM device was interesting and it produced a square shaped output but it also produced a rough textured wavefront.

The third quarter saw the production of more gratings of various description including an

on axis 1.06 cascaded lens. We considered several new projects related to substance detection and vehicle tracking. An 8 inch aperture multiply exposed focusing grating was made with about a 12 inch focal length. It worked as a wide angle telescope of sorts where 3 to 5 apertures overlap but at unique angles.

A 10 inch square grating was also produced for an experiment in indoor lighting. The grating turns blue light through 90 degrees and spreads the spectrum across the ceiling. The most interesting feature to us was the master, which was made to be used with P polarized light. Copies were intrinsically less noisy due to fewer interface reflections as Brewster's angle was approached.

In the struggle to make 1 degree gratings we began to win by making the film very thick. At 25 to 30 microns we at least had some hope of reaching our 30% efficiency goal, even though prior results at 1.5 degrees were only mediocre. In the meantime we got Big Red (HeNe) up and running again and tried a dozen more red sensitized DCG experiments using Jeff Blyth's recipes. We did not ever observe a significant increase in speed or quality over prior art but we found a significant improvement at low spatial frequencies in Green-Blue DCG by adding one of Jeff's components to it. In fact without this accidental discovery we would probably never have been able to make the 1 degree gratings.

By the fourth quarter Scott had discovered that the addition of Tetramethyl guanidine (TMG) to the gelatin will increase the index modulation in low spatial frequency gratings by a factor of 4 or 5. We added about 4 grams of TMG to 6 grams of dichromate and 30 grams of gelatin which enabled us to get more modulation than we needed by about 2 radians. The speed was good as well, the exposure was 10 mj / cm * cm and signs of thresholding were evident by the lack of the usual visible level of interference noise. Processing was 30 - 45 seconds in the tuning bath and 2 minutes development. The film responded best after aging at room temp for 24 hours, the dark reaction was slowed somewhat because the TMG also raised the PH.

Along with the 1 degree units we fabricated 5 ea 15 degree gratings in our 10-30-350 mix and 8 ea 4 degree gratings of .9 inch D. These were all shipped along with a few copies of the NV medal. Later we sent 5 more 1 degree gratings and more medals.

Scott continued much of Nov making and testing conformal mirrors with our new TMG doped film which we dubbed DCGG. He had been looking for a formula for film and processing that would yield consistent color, density and bandwidth centered at 546 nm. He was largely successful and made many conformal reflectors in his new films which also adhered better to glass and plastic substrates.

A proposal to tool up for IR CGH fabrication was completed by the last day of november. A sample sinusoidal IR grating cast in 15c was shipped with the IR proposal and the first week in december we had a transmission plot of the same material from 3 to 5 microns that showed strong absorption at 3 and 3.5 microns. We applied a 2 micron layer of 15c to the ZnSe and ran a spectrophotometer trace from 2.5 to 20 microns. Strong absorption was observed at 5.8

microns and between 8 and 9 microns and their was the previously observed substantial absorption at 3.5 microns. A copy of the output has been included with this report. The contribution of the substrate to the absorption spectra is negligible, the substrate was unfortunately dropped and broken at the university.

We obtained a few sheets of Dupont HRF 352 in Dec. and made precision gratings and reflection display holograms in it. In general we found it satisfactory for display work when enhanced with solvents and monomers but could not recommend it for a grating media. We wrote gratings of 400 and 1000 lines per mm and were unable to get faithful playback with respect to Bragg angle and random phase perturbations. At 400 lines the angular bandwidth was just under 3 degrees and the efficiency was 37% in the best samples. At 1000 lines the efficiency could reach 60% but the Bragg error, even in perpendicular gratings exceeded the angular bandwidth. The absorption in the blue remained strong after exposure and also after 10 hours under a 50 watt mercury arc lamp. The film thickness is 25 microns and the index modulation can be pushed to .06 or a little higher with some novel enhancement techniques. We also found that all of the UV curing epoxies that we routinely use cause wrinkling and other blemishes in all cases of laminating to glass or plastic.

In Jan 1990 I attended the computer generated HOE tutorial and learned more about the blazed binary structures being built at MIT. Gary Swanson made an excellent presentation and his notes contain many design relationships that I later included in my design guide brochure.

We managed to finish and ship four gratings ordered before our laser died for the fourth time in this contract. They were .94 inches in diameter by about .12 thick and diffracted the first order @ 2 degrees and about 20% efficiency. We also managed to coat most of the IR substrates that we received with sensitized gelatin mixtures. Three times we exposed and processed them and administered the tape test. The first time the germanium would not take a coating at all, and the MgF₂ and the ZnSe coated but failed the tape test. By the third try all three coated well and all passed the tape test except the MgF₂. We could probably find a way to make the MgF₂ stick better, a probable treatment would be a soak in nitric acid prior to coating plus the addition of TMG to the gel which in all cases so far has enhanced the adhesion of the gelatin.

We had our laser up and running with a new tube by the 15th of Feb and were able to complete 18 each 2 degree gratings of 20% efficiency. March first the Etalon heater control quit working but we had it repaired in a week.

I made some attempts at fabricating very low spatial frequency gratings for use in the IR in gelatin. A grating that diffracts 5 micron light at 4 degrees has only 14 lines per mm which is a spacing of 72 microns or about 3 mils. The angle required to expose at 488 nm is 6.8 milliradians or .39 degrees. It is not difficult to set up for these small angles but it can be hard to measure them. The grating structures have to be more than 2 wavelengths deep to achieve over modulation and ordinary processing will not produce those kind of depths. I tried etching with clorox but it was too difficult to control.

Another new technology was tried to make IR gratings rugged and very high transmission. The process has even been reduced to buying a prepared mixture called ACCUGLASS from Allied Signal and spinning it directly onto any flat substrate. Before it gels, and embossing master is held against it forming a grating in a an organic substance laced with glass atoms. After gelling the organics are baked out leaving behind a dense silicon oxide surface relief structure of "mill spec" durability. The big disadvantage is that the depth of modulation is limited to a fraction of a micron by the intrinsic shrinking characteristics of the polysiloxane solution as it becomes dense which limits practical use above the visible part of the spectrum.

We used our thickest DCG film formulae to make a .2 a .4 and a .8 degree embossing master linear sinusoidal grating. In general it was a successful effort and a copy of the .4 degree grating was shipped and should diffract at about 4 degrees near 5 microns. It is embossed on an acetate substrate so it will not be transparent all the way through the IR. We coated a half micron layer of "ACCUGLASS" (SILOXANE) 311 onto a Zn Se substrate and embossed a weak grating into it while it was still soft. We ran an IR trace on the coated substrate and have included a copy with this report but it is not likely to be useful because of shrinkage.

We made several novel anti aliasing (AA) filters by recording .2 and .4 degree gratings in a crossed configuration. All are simple embossed structures die cut from an acetate sheet. The idea behind them is to bleed a little image light onto all eight neighboring pixels without blurring the image. The net effect is intended to be to soften the aliasing effect, it has some support in the literature as an alternate method to using wave plates to deviate the image. The optimum bleed from Greivenkamp is 50 % and the optimum deflection would yield an effective pixel size exactly equal to the actual pixel pitch. Any larger displacements will still reduce aliasing artifacts but system resolution will suffer. After some study and consideration I am confident that it is possible to design and build a phase grating that will perform almost as well as conventional birefringent filters but if the criteria given in Greivenkamps paper, (applied optics, feb. 1990) are correct and complete it is not likely to ever outperform a birefringent filter. It does have a certain appeal in the IR where birefringent materials are scarce.

I purchased a Sony FDL-330 color LCTV for use in an HMD prototype, it has good contrast and a SBWP of 86400 pixels. It measures 2.14 by 1.6 inches and has square pixels about 6.5 mils on a side in an array of 360 by 240. We constructed dozens of off axis optics with and without power and tested them for use in a Helmet mounted display, some looked promising and others needed corrections. Flare light from the non conformal reflection optic with power seemed tolerably low, but of course the conformal units on spherical elements had the highest performance.

We wrote a new piece of custom software name ZONE that will make shaded zone plates on a laser printer. I have previously sent copies from the printer of a shaded zone plate with 15 zones and 21 grey tones and also a plate with 101 zones that is binary. The program also makes chirped linear plates .

The required depths of modulation for surface IR gratings of a certain efficiency can be determined from a Bessel function plot but not the optimum groove profile. From a plot the modulation for 30% efficiency is about 3 radians for sinusoidal gratings and yields 90% for sawtooth. The physical depth T can be found as a function of wavelength and equals wavelength divided by $(n-1)$. This yields about $.3 \lambda/\text{radian}$ for SiO_2 or UV glue or common plastics. This means we have to be able to emboss to a depth of about a 2 wavelengths for a max efficiency grating and to make "Diffractionmeter" efficiency gratings in the IR, (ratios of 3 or 4 to 1), we have to get to about $.7 \lambda$.

This implies that we will have to work in materials that are about 1, 4, or 8 microns thick depending on what part of the IR we are concentrating on at the time. The SiO_2 will not go on without cracking in layers of more than about a half micron, double coating may make it useful to 1 micron but it hardly seems necessary since many embossable plastics are good in the 1 to 2 micron range in thin layers. The UV cement we originally planned to use is good in 25 micron layers out to 5.8 microns with one serious dip at 3.5 microns so it is safe to use it in 2 and 5 micron thicknesses for the 1 to 2 micron range and the 3 to 5 micron range and I guess we will have to Ion etch an IRTRAN 2 (Zn Se) substrate for the 6 to 10 micron range.

We ordered in a fresh batch of Shipely S1400-37 positive resist and 351 developer and made master gratings 6 to 8 microns thick. Shipley is working on a new resist that will go on in 10 or 12 micron layers and they will keep me posted on availability. We made a master amplitude modulating transmission grating at 28.8 micron spacing and another at 57.6 micron spacing and then contact copied them into resist using a mercury lamp. We used the same procedure to make CGHs or Blazed Binary Optics.

The gratings are the correct period but we have not yet learned how to make a nondestructive transfer from photo resist to epoxy. A small piece of 15c embossed with 28 micron spacing is all that is left of a 2 inch square grating on glass. We have added a few intermediate steps such as the creation of a metal master to finally be able to transfer the embossed profile to an IR substrate.

We have learned that amplitude masters recorded in Illford green holographic film are far superior to masters recorded in Kodak high resolution plates. Evidently the higher resolution of the Illford film is necessary even for gratings of 28 micron spacing. This result was surprising to me but under a microscope a definite difference is observable in the masters and their copies, the Kodak plates recorded ragged looking fringes while the Illford fringes look smooth and sinusoidal. The copies of Illford into resist were dramatically better looking and better performing, the piece of embossed 15c is copied from a resist copy of the Illford film.

We also learned that exposing resist on a turntable can cause severe moire looking patterns to be generated in the resist, quite the opposite effect that I expected. The resist we are coating now may be up to 8 microns thick and requires 20 minutes to an hour in a Gyrex oven to dry sufficiently for exposure. The mercury lamp we are using for exposures is 175 watts and generates so much heat that we have to use forced air cooling to avoid melting the master and

resist together. Even with that much intensity we still must expose for about 20 minutes to get a 2 inch grating. Recipes for deep IR gratings which we will be given in this final report.

Our grating maker which consists of 3 rotary index tables and a fiber splitter delivery was completed to the point of functionality and a new program named ANGLES2 was written to determine the coordinates of the tables for successive exposures of volume or spatially multiplexed holograms. We then made a 40 shot interconnect HOE for MCC that effectively combined beams from 20 locations into one crossing zone without focusing the beams. It took two weeks of fabrication effort to get it right.

As a last project I finished off a bulky HMD using a two color flat conformal combiner and a large plastic collimator. It isn't much to look at but it is fed by a color LCTV with stereo headphones built in. We have quite a bit of experience now with making a curved combiner directly on CR4, so we can make a very compact binocular system. The big unit I made is something to work from, a crude base with a lot of improvements to be made. The most obvious change will be to design a binocular system rather than biocular to reduce the size of the optics. I think a good plan is to image the big screen on to a 1/4 inch image conduit and then rout the image over the top of the helmet to a small lens splitter and complimentary holographic collimator-combiners.

SUMMARY OF ACHIEVEMENTS

1. The addition of TMG to our standard film formula has resulted in the successful production of ultra low spatial frequency gratings (28 l/mm) in a volume material that remains closed to bonding agents. Gratings of this frequency can be capped and still retain most of their efficiency. All prior efforts to make such devices in DCG alone were unsuccessful.

2. The manipulation of the grating profile using a laser printer allows us to distribute power into just the few orders that we wish it to go into. Dammann gratings and Kinoforms and hybrid combinations as well as sinusoidal surface reliefs can now be made at our facility for infrared wavelengths or at spatial frequencies up to about 50 l/mm.

3. New subbing and coating techniques using nitrocellulose and TMG doped gelatin have produced Tricolor holographic reflectors on spherical polycarbonate and copolymer substrates. These substrates are necessary in goggles and helmet mounted displays. Dupont films were tested for the same application but were found so far to be inferior except for environmental stability.

4. A grating making machine was constructed using fiber optics and 3 rotary index tables. An optical interconnect HOE consisting of 40 spatially multiplexed gratings was made using the machine and some new software written for it. New parts including fiber couplers are being made to improve the machine.

5. We learned how to make sinusoidal and blazed gratings (kinoforms) in Shipely photoresist with etch depths of 3 to 5 microns. By contrast, the typical embossed display

hologram is less than .5 microns deep. The recipe is given elsewhere in this report, relief holograms were made in DCG also and replicated into plastic by casting and with pressure and solvents.

VOLUME HOLOGRAPHIC GRATINGS

The principle property that differentiates volume gratings from surface phase or amplitude gratings is a certain amount of angular selectivity. The Q of the grating is nominally related to the number of fringes a ray of light traverses when it is directed at the so called Bragg angle. For uniform thick gratings ($T > d$) with low index modulations ($\Delta n < .05$) the Q is high and only one order is usually diffracted. Conversely, it is possible to make gratings in DCG with very high index modulation ($\Delta n = .25$) so that efficiency is high even when $d=T$.

In any phase grating the efficiency of diffraction is a function of the phase shift at a wavelength plus an angular and polarization dependence at higher angles in deep relief and volume phase gratings and to a lesser extent in blazed structures. The power distributed in each order for a given phase shift is dependent on the shape of the phase shift or groove profile over each period of the grating. The required phase shifts for max power in the first order for three important shapes operating in the scalar or low frequency range are given below.

1. volume phase = 180 degrees, (30 to 99%) in first order depending on T/d ratio.
2. blazed grating = 360 degrees, (99%) in first order.
3. surface sinusoidal = 230 degrees, (33%) in first order.

A fourth type is the surface square wave that has no even diffracted orders and requires about the same modulation as the sinusoidal but can throw a little more power into the first order (40%). The 0 order goes to zero at 180 degrees.

The volume phase gratings we made most often are best described as scalar phase gratings, equivalent to surface phase gratings with all the same properties including the same power distributions in higher orders and virtually no angular or polarization sensitivity. They are completely without any surface relief and they have a gradient in the amount of modulation as a function of depth. Δn must equal $\lambda / 2 T$, where T is about 6 microns effectively, making Δn average about .05.

The scalar behavior is a result of operating at fringe spacings that are many wavelengths wide and the presence of higher orders and near lack of angular sensitivity is also due to the low ratio of film thickness to fringe spacing which is close to 1. These conditions require a high index modulation through the volume that must be large enough to offset the surface deformation that always occurs when molecules get packed more densely in the exposed regions. The surface phase grating is 180 degrees out of phase with the volume grating so that if it is weak then capping actually increases the efficiency but if it is strong then efficiency suffers dramatically upon capping. In practice it can happen either way and depends strongly on how it was processed.

An interesting change in phenomena takes place in volume gratings as the grating spacing gets larger and diffraction angles get smaller. If the index modulation is substantial then the whole structure looks like slabs of graded index material and the incident waves are refracted into the correct direction in the same manner as a GRIN lens would operate. The transition from diffraction to refraction is probably a smooth one and not very sudden but it is a topic that I have never seen in print and could make a very interesting analytical paper for an academic type. The efficiency of refraction type devices is generally unity but this case deserves close scrutiny on that point. The blazed optics we produced in a volume of gelatin were obviously simple grin lenses in the center where the diameter of the first zone was over 1 mm. The question is, when does the zone width to depth ratio cause the change from refraction to diffraction.

EXPERIMENTS

In all cases when we made gratings we were able to use conventional DCG formulations to get the required modulation with increasing exposure and processing as the grating spacing approached and became equal to film thickness. However, as soon as the spacing exceeded the thickness we ran out of dynamic range. The modulation was equal to about 1 radian and no amount of exposure and processing could boost it higher. At that time we stumbled onto TMG, which was being used in a red sensitizing scheme to make the film faster in the red while retarding the blue green sensitivity. It effectively replaced some of the gelatin molecules and we believe it increased the number of available crosslinking sites in the film. This could result in extending the dynamic range or maximum available unprocessed index modulation. Evidence of this could be observed directly by measuring the strength of two latent image gratings but as yet this has not been done.

The maximum processed modulation has been compared and found to be 3 to 4 times higher in 1 degree gratings. Increases are observable in high frequency gratings also but are not so dramatic and no improvement in speed is observed. Other benefits include better flow characteristics and coatings and much greater storage lifetime at room temperature, owing to the increase in PH that slows the dark reaction even in warm moist environments. The adhesion to glass is also nominally improved and the adhesion to plastic is greatly improved. The addition of TMG to our regular film formulae is also quite simple to accomplish. It is added with a pipette after normal preparations in small quantities until the PH reaches 7.

A common recipe used at Ralcon to make low frequency gratings is as follows:

A - mix together in 150 ml of water, 8 grams of ammonium dichromate, 30 grams of gelatin and 3 to 4 ml of TMG.

B - heat until completely suspended then filter and flood plate before spinning at 80 RPM for 4 minutes under clean warm air flow.

C - age for 24 hours at room temp then expose to 488nm radiation from 10 to 30 mj/cm*cm as needed to get required modulation.

D - Fix for 5 minutes , rinse 5 minutes, agitate for 30 seconds in each of 3 hot alcohol baths and blow dry with hot air.

The efficiency may then be further adjusted by going back through the water and alcohol baths for more or less time until the results are correct. Each time the efficiency is checked a cover slip has to be temporarily matched to the grating with xylene or an equivalent fluid to eradicate the surface grating.

Volume gratings made and capped in this fashion are very rugged and durable provided that they remain sealed at the edges.

They are also less lossy than surface type equivalents because they can be capped with AR coated cover slips. For application purposes they behave essentially as if they had a sinusoidal surface relief and in the worst case shift power around in their orders when tilted a few degrees.

The same gratings may be grossly overexposed and processed for much longer times to produce pronounced surface relief structures that rival photo resist quality. The main difference is that they are rugged enough to serve as contact copy masters for making replicas in plastics softened by solvents. Alternatively they may be metalized in a vacuum or in a non aqueous solution and built up into hot press shims. We have used them routinely as masters for replication directly into acetate using a drop of acetone and a pair of hand cranked nip rollers.

LOW SPATIAL FREQUENCY GRATING Fabrication Procedures

One set of requirements from NVL is for two types of gratings for use in the 1 to 5 micron region and in the 8 to 12 micron range. One is to have a spatial frequency of 17.4 lines per millimeter and the other is to have a frequency of 34.7 lines per millimeter. the tolerance is +/- two lines per millimeter (+/- 0.056 degrees at 488nm or +/- 0.072 degrees at 632.8nm). The diameter is 43 mm +/- 1mm and thickness is 2 mm +/- .5 mm for the 1 to 5 micron range, and 44.5 mm diameter and 3.2 mm thk. for the 8 to 12 micron range. The master gratings were written at 488nm and checked at 632.8nm. The full writing angles was 0.970 degrees and 0.486 degrees. The full "checking" angles was 1.260 +/- 0.072 degrees and 0.630 +/- 0.072 degrees. The checking was done on a rotary index table with 30 sec resolution (.008 degrees).

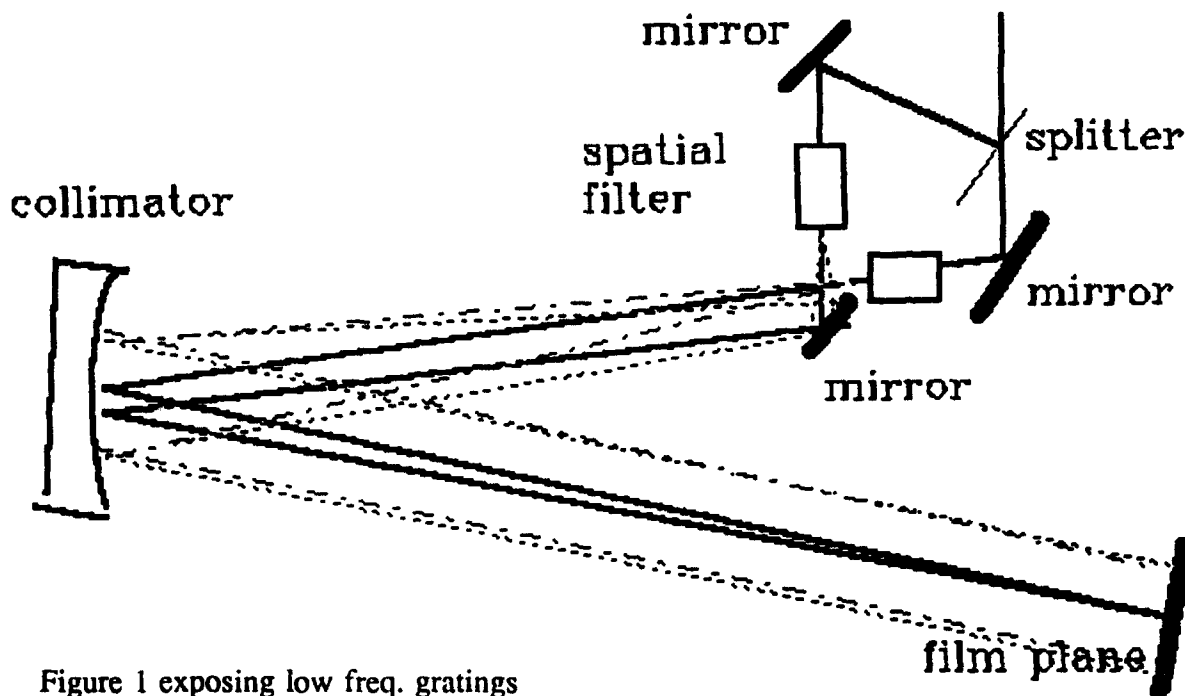


Figure 1 exposing low freq. gratings

Attempts to make these gratings in DCG or DCGG were less than successful so we decided to make the desired gratings in Silver Halide film and then contact copy them onto photo-resist. The films we are using are KODAK High Resolution Plate, Type TE and ILFORD Blue/Green Sensitive Holographic Film.

KODAK PLATES

- 1) Exposed using 488nm at $2\text{mW}/\text{cm}^2$ for one second .
- 2) Developed in fresh DEKTOL for 1,2,3,4,& 5 minutes to yield five different densities. The low densities produced binary type gratings (high contrast square wave, odd orders only) while the higher densities produced the desired $\sin^2$ gratings (medium to low contrast).
- 3) Used standard KODAK Stop-Bath, Fixer, and Photo-Flow wash to finish the process.

ILFORD FILM

- 1) Exposed using 488nm at $1\text{mW}/\text{cm}^2$ for one second.
- 2) Developed in fresh DEKTOL in increasing increments of 20 seconds to generate a series of different densities. Note that none of the ILFORD gratings created the characteristically brighter odd orders that indicate a near binary grating.
- 3) Used the standard KODAK Stop-Bath, Fixer, and Photo-Flow wash to finish the process.

The resulting gratings were checked at 632.8nm and found to diffract a beam at 0.632 degrees and 1.233 degrees. (corresponds to 17.4 and 34.0 line pairs per millimeter). The grating spacing was also measured on a 20 power optical comparator and found to be 57 microns on one and about 29 microns on the other. The copy work was done using the 29 micron grating because it turned out to be more in demand.

We used SHIPLEY #1400-37 PhotoResist spun onto 2.5 X 2.5 inch glass squares for making the surface-relief copies of the Silver Halide masters. As we had no previous experience with this photoresist, we called the Shipley Company for instructions. Here's what we got:

- 1) Work under yellow light with no ambient radiation shorter than 500 nano-meters.
 - 2) Clean the substrates and bake them dry at 200 degrees centigrade for at least ten minutes. Cool the substrates in a dry atmosphere.
 - 3) Spin coat the substrates at 2,000 to 3,000 rpm until the coating is dry. This will yield 3u to 5u coatings.
 - 4) Soft Bake the coated substrates at 95 degrees centigrade for 45 minutes and then cool them in a dry atmosphere.
 - 5) Contact Copy the Silver Halide master with broad-spectrum Ultra Violet radiation. The UV must be collimated and it will take approximately 150 milli-joules per square centimeter.
 - 6) Develop the resist for 60 seconds in MICROPOSIT 351 DEVELOPER CONCENTRATE diluted 3.5 to 1. Maintain the temperature at 21 +/- 1 degree centigrade.
- * Fix the developer concentration and the development time. Make your adjustments to the exposure time as this directly controls the solubility of the resist.
 - * Agitate **NO MORE THAN** two to three seconds when placing the resist into the developer.
- 7) Gently rinse the developed PhotoResist with D.I. water and gently blow it dry with warm, not hot, air.

+++Heres what worked:

- =====
- 1) Set up the Gyrex IR oven with the low pre-heat on, the main heater control set to position seven, and the conveyer speed set to slowest. While the oven warms up, wash the substrates, rinse them in D.I. water, and dry them in a class 100 clean hood. When the substrates are dry, run them through the I.R. oven two or three times to dehydrate them.

Keep the clean,dry substrates in a clean hood until ready to coat.

2) Cool down and set up the I.R. oven for the "Soft Bake" step. The pre-heater is turned off, the heater is set to one,(130 to 140 degrees F) and the conveyer is set to its slowest speed (6 minutes). When you 'soft bake" the photoresist, you will run it through the oven only twice in succession. Over-baked resist won't react to light.

3) We use a multiple discreet speed DC spin-coater with a small suction cup for applying the photoresist. The speed control is set to twelve to get approximately 900 revs per minute as measured by a mechanical tachometer. The spin coater box is lined with aluminum foil to make cleaning up easier and safer and the whole set up is on a class 100 clean bench. To actually coat the resist, center a substrate on the suction cup and apply 3ml of the resist to the substrate. Next, tilt the substrate/suction cup so as to spread the resist evenly over the surface to be coated. Lastly, attach the suction cup to the spin-coater and spin the coated substrate for three minutes.This will produce a dry 6 micron thick coating as measured by a .001 inch resolution dial indicator, (2.5 microns per division).

4) After a substrate is coated, immediately run it through the oven for the soft bake step. If all the substrates are coated before baking them, they will go into the oven with differing amounts of retained volatiles and the final product will have non uniform sensitivity to light. Remember to run the coated substrates through the oven twice to completely bake out the volatiles and obtain the highest sensitivity to U.V.

5) To make a contact copy of a silver-halide master, we place the master with the emulsion side up onto the photoresist and weight the master down with a half inch thick slab of suprasil. Next we place a non-reflective mask over the suprasil to prevent edge scattering and reflections. Lastly, we expose the whole works to a standard 175 WATT mercury vapor yard light from which the outer glass globe has been removed to allow the full spectrum of UV to escape. Thirty minutes at a distance of one foot worked quite well for us and the lamp had to be fan cooled at that distance or it would melt the plastic.

6) The development process consists of washing the exposed photoresist off of the substrate with a dilute solution of MicroPosit 351 developer (more commonly known as sodium hydroxide). We used a solution of three parts water with one part of the MicroPosit 351 Developer Concentrate. Development is carried out in a small tank by uniformly immersing the plate and gently agitating only two times back and forth and then letting the plate lean against the side of the tank film side down. After developing the exposed resist for four minutes, we then rinsed it in a dilute solution of Kodak stop-bath (3 ml per 500 ml total volume) and then De Ionized water for ten minutes. We tried using photo-flow in the rinse water but it tends to leave a residue. Dry the finished gratings in a clean hood under a gentle flow of air. DO NOT blow dry with high pressure air, the grating is easily blown apart at this stage.

7) When we tried hard-baking the gratings in the Gyrex oven and succeeded in melting

the resist. We now skip the hard-bake step as it does not seem to be necessary for electroplating either.

8) We have exported the resist masters to Dazzle for electro plating but we are preparing to do our own plating in the future. Electro plating is necessary to replicate onto IR substrates using UV epoxies or thin plastic films.

RECENT RESULTS

We received 8 shims from two different resist masters made at 28 microns from Dazzle Enterprises. The shims were made in 4 different thicknesses, 2, 4, 6, and 8 mils thick and were not as flat as we had hoped. Casting against them was carried out as follows.

1. The shim was coated with silicone mold release and wiped off with a printers pad.
2. A small pool of 15C epoxy was poured onto the shim and a substrate of 7059 glass was cleaned and dropped onto the pool and shim.
3. The assembly was clamped between two 1/4 inch thick glass discs and held close to a UV source until well cured.
4. The shim was pulled slowly from the epoxy and the casting checked for diffraction properties.

The grating was well transferred in all trials but it was not possible to maintain good optical flatness with any of the shims. We always got substantial ripple in the epoxy, probably more pressure would help and that approach will be tried with a 2 part epoxy and a pair of metal blocks next. Copies were also made into plastic substrates using a solvent (acetone) and the pressure of a pair of rubber nip rollers. These copies did not suffer any ripple flaws because only the surface was softened and deformed to record the grating.

SPECIAL SURFACE GRATINGS

In practice most of the gratings formed interferometrically come out sinusoidal in shape, the exceptions being a special geometry for making blazed structures and the use of multiple phase locked sources to make rounded cells. In theory it should be possible to make many different profiles via the coherent addition of multiple waves at correctly calculated amplitudes and angles. Probably the very consideration of the difficulties of controlling the angle, phase and amplitude of a dozen waves at a time spawned the invention of the computer generated hologram.

The two most important profiles are the stepped square wave and the ramped or blazed profile. More recently the ramp has been fabricated as a series of small steps or as a changing dot density. Blazed profiles are well known for their high efficiency and bandwidth in both gratings and zone plates. Square gratings have been popularized in a special additive form by Dammann to be used as array generators in one or two dimensions.

BLAZED BINARY OPTICS

The term Binary Optics is derived from the use of just two phase shifts used to fabricate the gratings, usually 180 degrees and zero. In the case of a blazed phase grating (also known as a kinoform) the correct shift is 360 degrees from the highest to the lowest point and it is the same for each annulus of a zone plate as well as each line of a grating. This binary ramp may be machined into a substrate, exposed with multiple binary step masks or exposed through a pseudo grey scale transparency of the desired geometry. Because of the applicability to low spatial frequencies and the low cost to implement we chose the pseudo grey scale mask approach to address design problems in the IR. We made up and use the term blazed binary optics because the blaze is actually produced from a digital or binary dot density pattern that approximates a linear or similar transmission slope between zones or fringes. The dotted transmission slope is blurred in a camera and copied into a phase relief or volume phase material to approximate a kinoform.

Essentially we create a large fringe pattern on paper and then photo reduce it to the dimensions that will diffract light at the correct angles. This is a very old technique, probably the first computer generated fringe patterns were actually drawn by hand and photoreduced. The patterns we have produced so far have been simple circular zone plates with as many as 20 levels of grey between zones. These have been calculated and plotted on a 300 DPI laser printer, the calculations were done at 2400 DPI but we have not yet tested the higher resolution master. Certain periodic artifacts creep into the pattern as the limits of resolution are approached so we would be wise to use the higher resolution masters for any practice project.

As was demonstrated with the sinusoidal gratings it is possible to make the equivalent of a blazed grating in a volume media provided that the index modulation can be achieved. Indeed we did try this and found that in 50 micron layers of DCGG we could get sufficient modulation to diffract about 25 percent of the light in a 15 1/mm structure. The draw back is that it takes 24 hours to process a piece of 50 micron gelatin because of the slow diffusion rates. We are trying some polymers from Dupont in the same application. These structures are definitely acting as graded index wave guides in some or all of the zones.

In photo resist we have succeeded in making good smooth relief images that actually are over modulated and thereby diffract much of visible input light into higher orders indicating a groove profile with a bit to much elevation for the visible spectrum. We

made lenses (zone plates) that have a focal length of about 20 cm at 633nm for use eventually as bifocal contact lenses.

One of the obvious advantages of this whole approach is that special patterns may be readily achieved. As an example, a blazed grating may be designed with one grating structure riding on top of the other so that two waves are diffracted, both on the same side of zero while no energy is lost on negative orders. This would be hard to achieve any other way except at sufficiently high frequencies in double exposed thick volume gratings. High energy elliptical zone plates for CO₂ lasers have been made this way by a group at Loughborough.

DAMMANN GRATINGS

H. Dammann and K. Gortler introduced the idea of using special binary phase gratings to make arrays of uniform intensity spots in 1971. For practical reasons related to computation and to fabrication, the largest arrays that can be designed and constructed are about 40 by 40 spots. Dammann gratings are computed using nonlinear optimization and the success depends on selecting a good start value for the positions of the phase transitions that must be made in each period of the grating. These phase transitions can be thought of as overlapping identical gratings that are "pulse width modulated".

Qualitatively a Dammann grating may be thought of as a very low spatial frequency binary phase grating with an appropriate number of properly placed bumps to generate phase transitions in each period to alter the power distribution from the classic odd harmonic decreasing pattern to a uniform N harmonic pattern. The most obvious bump would be one placed right in the middle of the period to fill in the 2nd, 6th, 10th and so on orders. The next step might be to put one on either side of that to increase power in the 4th and so on but there are actually 2 to the N solutions to a grating that is to have $2N + 1$ equal outputs. Some solutions may require placements of bumps that are beyond the fabrication capabilities of modern VLSI techniques so not all solutions are practical.

It is also proper to view the Dammann grating as a superposition of several identical phase gratings shifted a precise amount laterally with respect to each other. The design goal being to calculate a shift that generates the correct power distribution and is fabricatable. It should be noted that the efficiency of these gratings can be very close to 100%. Some power will always be lost in higher orders but they are very good in practice as well as theory.

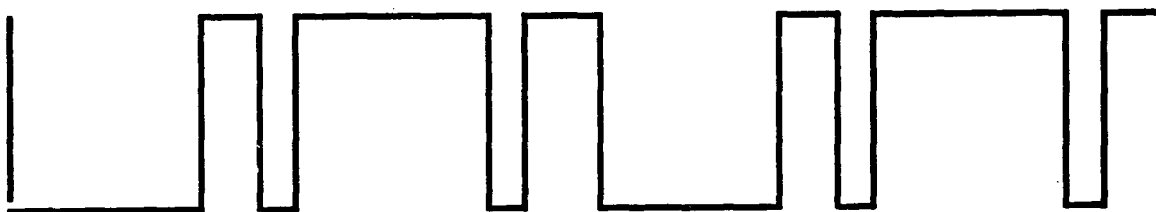
Another way to generate a Dammann grating is to interfere the light from a perfect array of coherent sources. This is really an unlikely possibility because of the precision required in placing the sources, controlling their phase and in collimating all the sources through a lens without introducing enough aberrations to displace a fringe. The required precision is in the submicron range and in fact should precisely equal the precision of fabricating the grating mechanically.

The complex amplitude transmittance of the Dammann grating is the fourier transform of the amplitude distribution in all its orders, and vice - versa. The design does not have to be symmetric and it does not require a binary phase shift, the choice of a 2 level phase shift is made only to facilitate fabrication. It can then be made using only one mask.

One of the most novel uses of the Dammann grating is to combine the outputs of an array of lasers by literally putting them all in one cavity. This technique was introduced by Veldkamp of MIT in 1982 at an OSA meeting in Hawaii. He demonstrated the coherent combining of 6 diode lasers which all oscillated off a common output reflector. His grating used a 180 degree phase shift and 4 phase transition points in each period and was 85 % efficient.

We have not as yet designed or constructed a Dammann grating but we have the capability to make them up to resolutions of 50 l/mm. This limitation would seem to limit the base grating frequency to less than 13 l/mm which corresponds to a diffraction angle of about .4 degrees in the visible. For the combining of closely spaced laser arrays this may be a desirable angular range. If so then we could probably make useful devices with our laser printer - photo reduction process. Computing the phase transition positions would be a problem at present but we could do it in a relatively short time using help from USU. An example of a Dammann grating profile is given below.

180 degree phase shift



0 degrees phase

period 1

period 2

Figure 2 1 dimensional Dammann Grating

GELATIN ON PLASTIC SUBSTRATES

All through the past 2 years we have been experimenting with new film formulas and with the application of gelatin and other polymers to plastic and IR substrates. We have been successful in making gelatin stick to polycarbonate and some copolymer substrates and to several IR materials. The plastics are important to us because laser protection eyewear and helmet mounted displays have to be fabricated from them.

Accomplishments

We have developed five different methods for subbing plastics to make them retain DCG. Two of the methods involve applying a cellulose based coating to the substrate and then stripping off a sub-group. This gives the gelatine something to hold on to. An easier method is one where you just immobilize some amino group or a portion of a gelatin chain on the surface of the substrate. This way, since the resulting "coating" is only a molecule thick, you don't have to worry about getting it optically flat like you do with the cellulose based methods. Also, this type of subbing makes the hologram an integral part of the substrate rather than just a coating. This latter type of subbing works very well with CR-39 while the co-polyester requires a nitro-cellulose subbing with the nitro group stripped off.

Scott had to come up with a couple of new film formulations to maintain compatibility with the subbing methods above. In addition, the new formulations had to enable a large shift in spatial frequency while maintaining a relatively narrow band-width. To get the frequency shift, he ended up cutting down the amount of ammonium dichromate and experimenting with more dense dichromate salts. This worked because gelatin, like cellophane, never quite shrinks back to it's original thickness after being swollen with water. By using less of a more dense dichromate salt, this natural swelling was not counter-acted by the removal of excess mass (salt) from the DCG during processing. To maintain a narrow band width, he modified the gelatin to provide more sites for cross linking adjacent gelatin chains by adding TMG. This inhibits differential swelling in the gelatin and minimizes any chirp in the spatial frequency of the HOE.

II. DIFFICULTIES ENCOUNTERED

The number of different types of plastic samples that were tried as substrate materials has, so far, multiplied the amount of development work for this related by five.

With the exception of one case, all of the spherical surfaces provided by customers had some unknown substance absorbed into their curved surfaces. This substance is then absorbed by DCG during processing and prevents the formation of a hologram. We are not yet sure how this works, but we suspect that this substance acts like a plasticizer. This would keep the DCG soft in the dry alcohol baths and allow the fringe structure to collapse as the gelatine is dried. This theory is supported by the fact that the DCG samples removed from these domes after processing were tough and flexible while normal DCG tends to be hard and brittle after processing.

We have a second surface mirror with the necessary radius of curvature for a useful HMD HOE and we worked out two methods for silvering it's first surface. One method gives a hard chrome-silver alloy coating. Unfortunately, both of these types of coatings need to be polished for use as a first surface mirrors and are there fore not optically flat enough for holography. We are now experimenting with pure chrome plating in order to get a surface that does not require mechanical polishing.

Later on we will be able to aluminize surfaces in house as we have just purchased a bell jar vacuum system. It will not be operative for some time because of missing or inoperative components such as a heater boat and some aluminum stock.

IV. FORMULATIONS

Subbing Method One Dilute Collodion, USP, one to one hundred with methanol. Filter this solution, if necessary, and then carefully coat the desired surface. Let this coating dry for several hours in a clean environment and then coat the substrate with DCG in the normal fashion. This method works well for stiff substrates and/or small surfaces.

Subbing Method Two Sub the substrate as in method one but before coating the substrate with DCG, soak it in a one to one solution of ethanol and ammonium sulfide for thirty minutes. Keep the substrate wet until it can be coated with DCG. This method provides a much stronger bond with the gelatine which is necessary for large or flexible substrates.

Subbing Method Three Clean the substrates and then soak them in a strong ammonia solution for one to two hours. Then, put the substrates into a solution of tetramethyl guanidine (20ml), water (80ml), and ammonium dichromate (0.25g). Warm the solution to sixty degrees centigrade and let the substrates soak. After three or four hours, the substrates can be rinsed off and coated in the normal manner.

Subbing Method Four Clean the substrates and soak them in a strong ammonia solution for several hours. While the substrates are soaking, cook up a solution of thirty grams of gelatin, three hundred milli-liters of water, five milli-liters of tetramethyl guanidine, and ten grams of ammonium dichromate. When the substrates have finished soaking, chill them in a freezer and then dip them into the gelatine solution to coat them. Place the coated substrates on a sheet of glass and set them in bright sunlight or under a U.V. lamp for a day. After they have been thoroughly exposed, wash the substrates off with hot water and then coat them in the normal manner.

Subbing Method Five Some plastics can be coated with DCG after soaking them in sulfamic acid for several hours and then in a strong ammonia solution for several more hours.

DCGG with a Built In 60nm Shift In two hundred milli-liters of cold water, dissolve two and three fourths grams of ammonium dichromate and one and a half milli-liters of tetramethyl guanidine. Suspend thirty grams of gelatine in this solution and then slowly heat, with constant stirring, the solution to sixty degrees centigrade. Coat and age this emulsion in the normal

manner. Air-gate exposures of twenty five to fifty seconds with one milli-watt per square centimeter at 488nm should produce efficient holographic reflectors of the 546nm line.

Glass Silvering Formula One

I. The Silvering Solution

- A. Make a 6% solution of ammonia in water by mixing 5ml of stock 30% reagent Ammonium Hydroxide with 20ml of D.I. H₂O. You will probably use about 20ml of this solution.
- B. Dissolve 4.38 gm Ag NO₃ in 50 ml of H₂O.
- C. Add the 6% Ammonia solution to complete precipitation & then to almost, but not quite re-dissolve all of the precipitate. The object is to make a saturated solution of silver azide.
- D. Let the solution stand for one to two hours, filter it, and q.s. to 500 ml with H₂O. Store it in a brown bottle, preferably in the dark.

II. The Reducing Solution

- A. Dissolve 1.83 gm AgNO₃ in 10 ml H₂O & set it aside.
- B. In a 500 ml to 750 ml flask, dissolve 1.10 gm Rochelle salt in 50 to 75 ml of water and heat the solution to boiling.
- C. To the boiling solution, add 1 ml of the solution from II.A. and let the boiling continue for three or four minutes.
- D. Let the solution cool and then filter it. Q.S. the filtrate to 500 ml with H₂O.

III. Silvering A Plate

- A. The glass must be ABSOLUTELY CLEAN. Scrub it good and soak in 50% HNO₃ for several hours. Then wash off with D.I. H₂O and dry in a CLEAN environment.
- B. Use a container with an area that is just larger than the plate you wish to silver. The container should be clean plastic or dirty glass to facilitate cleaning.
- C. Mix equal parts of the reducing and silvering solutions in the silvering container and support the plate to be coated so that the surface to be coated is just in contact with the solution. Dropping it to the bottom will yield a schlock coating that will not adhere well.
- D. Leave the plate in the silvering solution till the solution clears and then remove it without

touching the silvered surface. Rinse the plate thoroughly with D.I. H₂O and then let the plate air-dry in a clean environment.

- E. When the plate is dry, expose it to U.V. for 12 to 24 hours. (bright sunlight at 5000 ft. altitude works really well.) This last step is necessary to harden the silver and make it adhere well to the glass.

IV. RESULTS

- A. This method makes a great second-surface mirror with a minimal amount of work. If the glass isn't absolutely clean, you tend to get pin holes in the coating. The coating is quite thin and if you try to polish it to get a first surface mirror, you will remove flakes of silver. To protect the coating, you will need to coat it with lacquer or shellac or something.

Glass Silvering Formula Three

I. Solution Preparation

- A. Dissolve 10 grams of silver nitrate and 0.2 grams of potassium dichromate in 100 ml of DeIonized water. Add 6% ammonia in water until the turbidity first produced is cleared. (dilute 20 ml of 28 to 30% ammonium hydroxide with water to 100 ml total volume. You will use approximately 50-60 ml of it in this step.) Save the rest of the ammonia water; you will need it.
- B. Make up 100 ml of a 9% Potassium Hydroxide solution by dissolving 10 grams of Potassium Hydroxide in 100 ml of DeIonized water.
- C. Make up 100 ml of a 2% glucose solution by dissolving 2 grams of glucose in 98 ml of DeIonized water and then add 2 ml of methanol.
- D. Have on hand a weak (2 to 5%) solution of silver nitrate in water. The best case is to have it on hand in a dark glass dropping bottle.

II. Glass Preparation

- A. Scrub the glass (8" x 10" for this much solution) thoroughly and then soak it in a strong solution of Sodium Hydroxide for several hours.

III. All Together Now...

- A. Add the Potassium Hydroxide to the Silver Nitrate solution with continuous stirring and, while still stirring, add 6% ammonia solution drop-wise until the solution is just clear. Approach the endpoint slowly as it is easy to overshoot due to the slow re-solution of the chromic

precipitate.

B. Add a few drops of weak silver nitrate solution to the above solution until the solution is just turbid.

C. Add the Glucose solution and pour into the coating tray. QUICKLY rinse off the glass plate and put into the coating tray so that the surface to be coated is just in contact with the liquid and there are no trapped bubbles.

D. Slowly rock and/or jiggle the tray for twenty minutes to half an hour and you should have a hard, even coating of silver and chrome. Note that the rocking is necessary to produce an even coat and that additional time in the coating solution will (up to a point) produce a thicker coating.

E. When the coating is complete, quickly, but thoroughly, rinse the plate with distilled water and allow it to dry thoroughly. Allowing the plate to sit in bright U.V. so that the U.V. can hit the glass/silver interface will make for a stronger bond between the silver and the glass.

OPTICAL INTERCONNECT HOES

We have been working out ways to make spatially and volume multiplexed gratings for a long time. We made multiple facet holographic gratings several years ago on the most reliable assembly of machinery made to that date. One of the most serious shortcomings of that system was the need to keep many reflecting surfaces clean, flat and undamaged. It proved to be an almost impossible chore. Another more inherent to the design problem was that any change to the elevation angle introduced a rotation of the polarization and only one elevation angle was changeable between exposures.

Since then we have experimented with single mode fibers and two types of splitters and fiber launch methods. The fibers have severe stability problems prohibiting long exposures without active fringe stabilization but we are only making small gratings which can almost always be made in less than 1 or 2 seconds. The average drift of the fibers we have tested is only a half a fringe in 30 seconds in a reflection geometry. The gratings we will make most often are 4 times less sensitive to drift and should not be a problem to make.

We have assembled all the parts to make a system of moving arms that can position the fiber ends in elevation and skew with accuracies of possibly 30 seconds of arc. In addition we can move a mask over the film with 1 mil resolution in two axes or move the holographic film under a mask. The fiber system first chosen and tested was assembled mostly in house with Andrew D fiber which is so small (1x2 microns) that only 20% of the incident light even at 488nm can get into the fiber. The system worked well but we have already broken a fiber off from a grin lens and may not be able to repair it correctly.

A second system complete with splitter assemblies is being made for us by OZ optics of Ontario, Canada. The people at Radiant Communications that helped us with our original device are no longer interested in making custom assemblies so we are on our own with the D fiber device. The OZ system uses a much larger fiber and will allow as much as 80% of the input light to be launched. We are looking forward to hooking it all up in the near future to make a few interconnect gratings for RADC and possibly for someone at NVL.

A new piece of software has been completed and dubbed ANGLES2, it computes the input coordinate of three rotary index tables to set the elevation and skew of each successive exposure. Without such a program we would be forever figuring out how to convert between wavelengths and input angles or positions. Dave Twede is largely responsible for the program. It enables us to compute and set both elevation angles for any wavelength plus a skew angle which is set by rotating a stage holding the film.

A sketch of the exposure system is given below. All the angles are set from the front of the machine and small LED lights placed over the veneers help set each angle with advertised accuracies of 10 seconds of arc. We have tested the hardware and found it to be stable enough for reliable recording of transmission gratings at a minimum.

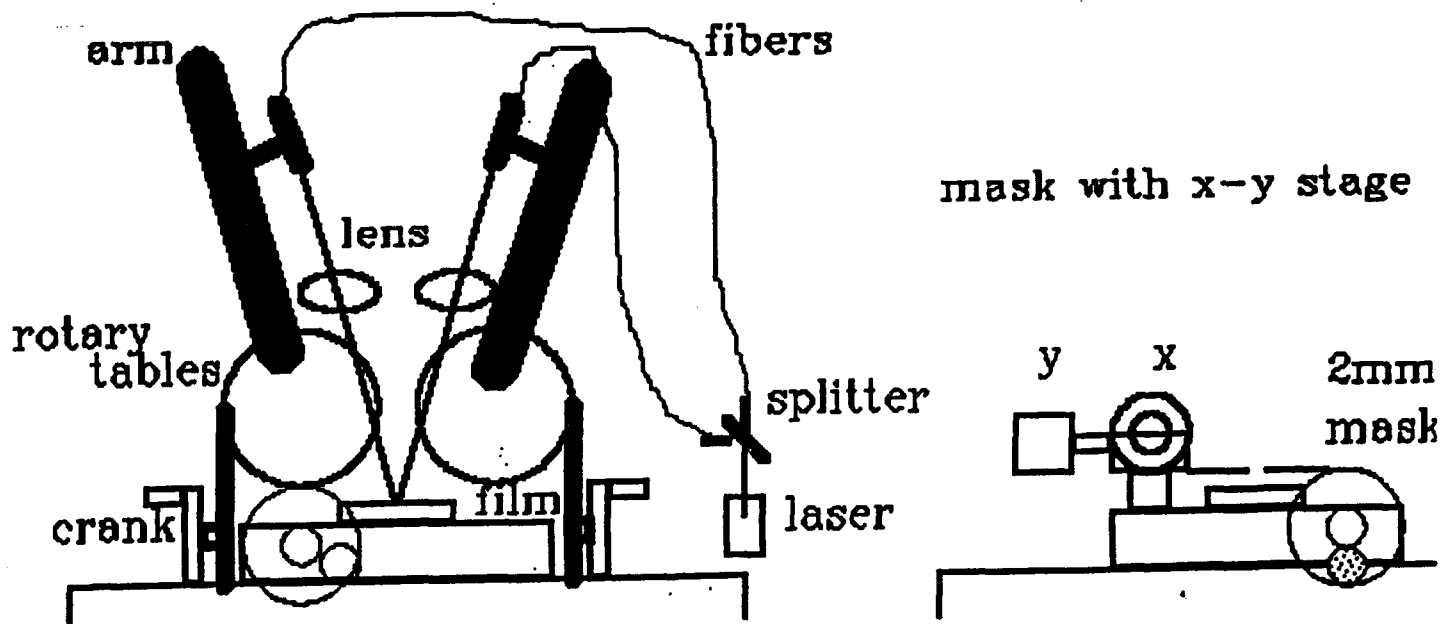


Figure 3 Grating multiplexer and mask alligner

Concluding Remarks

We have progressed steadily in capability and capacity during this contract period. We are now able to deliver a wider range of holographic optics than before and have advanced the state of the art in the making of low spatial frequency volume holographic gratings. We have incidentally patented a technique for enhancing photopolymers and have made deep surface relief grating structures in photoresist, epoxy and plastic. We have developed new and novel ways to get gelatin to stick to plastic and have made three color reflectors on plastic substrates. We can now make complex optical interconnect HOEs and we made a possibly useful anti aliasing filter for the near IR.

Attempts at making some white light viewable reflection holograms of multiplexed maps resulted in a decision to abandon that method of display for the current format at least and a hologram of a range finder turned out less than spectacular also. We had many reorders for low frequency volume gratings so we must have done that best of all or else somebody at NVL broke a lot of glass. Few if any of the original goals of phase two were met, but they were not of particular interest to the NVL and were best abandoned. Money and time were spent on production equipment at times but prototyping or development work remains the main interest and function of this lab with small production runs only being accommodated.

Nevertheless we are equipped and ready to continue to supply specialty HOE devices to NVL in a phase three effort in whatever quantity is needed. We hope our services have been appropriate and that we have developed something useful in the past 3 years. The commercialization of these and similar products has been slow but as a result of the variety of work done so far we are now offering an 8 piece HOE kit to the appropriate market of educators and investigators, engineers etc.

Acknowledgements

The principle investigator was Richard Rallison assisted by Scott Schicker, Steve Bialkowski and David Twede as chemists, programmers, and holographers. Jeff Brown aided us with some special electronics and Dwight Olsen and Chris Nielsen made film and performed many lab chores for us. Tana Clark helped with reports and administration. We also had input at various times from Mike Morris of the U of Rochester and from Gary Swanson of Lincoln Labs at MIT. Mark Norton of NVL initiated most of the work, input some of the design information and was the technical officer for the contract.

RDR

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This is LPMM DEG.MCD, a MathCadd template which compares read/write angles with the resultant LINES PER MILLIMETER (sometimes referred as line pairs per millimeter) of a holographic diffraction grating.

Given the grating equation, $\lambda = 2 \cdot d \cdot \sin(\hat{U})$, we can define the functions

$$d(\lambda, \hat{U}) := \frac{\lambda}{2 \cdot \sin(\hat{U} \cdot \text{deg})} \quad \text{and} \quad \hat{O}(\lambda, D) := 2 \cdot \text{asin} \left[\frac{\lambda \cdot D}{2 \cdot \text{mm}} \right]$$

where D is Lines Per Millimeter, λ is the wavelength of interest, $\hat{U}$ is the angle between the normal and the input/output beams, and $\hat{O}$, (equal to two times $\hat{U}$) is the angle by which an input beam is diffracted by the holographic grating.

Then, let $\lambda := 632.8 \cdot \text{nm}$, $\hat{U} := 0.5, 1 \dots 12$, $D := 20, 40 \dots 500$,
 $\text{nm} \cdot 10^{-9}$, $\text{mm} \cdot 10^{-6}$, $\text{mm} \cdot 10^{-3}$, $\text{deg} \cdot \frac{1}{180}$

$\hat{O}$ (deg)	fringe spacing (microns)	spatial frequency (lines/mm)	spatial frequency (lines/mm)	fringe spacing (microns)	$\hat{O}$ (deg)
	$d(\lambda, \hat{U})$	mm		$\frac{1}{D} \left[\frac{\text{mm}}{\text{mm}} \right]$	$\hat{O}(\lambda, D)$
$\hat{U} \cdot 2$	$\hat{U} \cdot \text{mm}$	$d(\lambda, \hat{U})$	D	D	deg
1	36.26	28	20	50	0.725
2	18.13	55	40	25	1.45
3	12.09	83	60	16.67	2.176
4	9.07	110	80	12.5	2.901
5	7.25	138	100	10	3.626
6	6.05	165	120	8.33	4.352
7	5.18	193	140	7.14	5.078
8	4.54	220	160	6.25	5.804
9	4.03	248	180	5.56	6.53
10	3.63	275	200	5	7.256
11	3.3	303	220	4.55	7.983
12	3.03	330	240	4.17	8.71
13	2.79	358	260	3.85	9.437
14	2.6	385	280	3.57	10.165
15	2.42	413	300	3.33	10.893
16	2.27	440	320	3.13	11.622
17	2.14	467	340	2.94	12.351
18	2.02	494	360	2.78	13.081
19	1.92	522	380	2.63	13.811
20	1.82	549	400	2.5	14.542
21	1.74	576	420	2.38	15.273
22	1.66	603	440	2.27	16.005
23	1.59	630	460	2.17	16.738
24	1.52	657	480	2.08	17.471
			500	2	18.205