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Extremely Narrowband Cascaded Holographic Adjustable Range Tunable (ENCHART) Filter

Final Report

Contract No. N00014-95-C-2011

Period of Performance: 11/08/94 to 08/08/95

Presented to:

Naval Research Laboratory
4555 Overlook Avenue SW
Washington, DC 20375-5326

Technical Monitor:
Dr. Judith Lean
Code 7665

Presented by:

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Principal Investigator:
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December 1995

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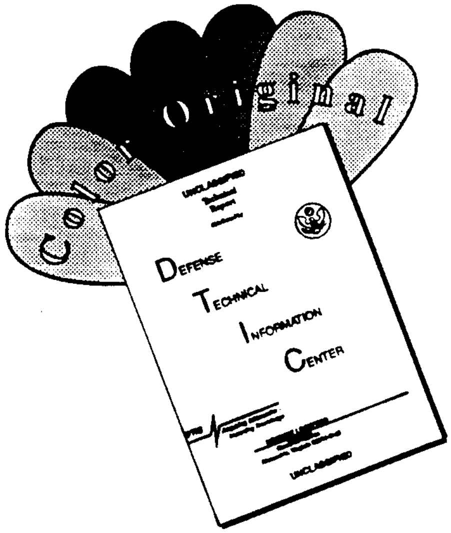

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POC Physical Optics Corporation

January 5, 1996

Naval Research Laboratory
Code 7673L
Attn: Dr. Judith Lean
4555 Overlook Ave. SW
Washington, DC 20375-5326

Reference: Contract #N00014-95-C-2011
"Extremely Narrowband Cascaded Holographic Adjustable Range Tunable (ENCHART) Filter"

Dear Dr. Lean:

Enclosed please find the Final Report and Final Patent Report DD882 for the above referenced contract.

If you have any questions or need additional information, please do not hesitate to contact me.

Sincerely,

Olivia Tu
Legal & Contracts Administrator

OT/pl
Enclosure (4)
cc: Code 7605.10 (1)
ACO (882-4)
DTIC (1)
Ref: 3303

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POC #3303

REPORT OF INVENTIONS AND SUBCONTRACTS

(Pursuant to "Patent Rights" Contract Clause) (See Instructions on Reverse Side.)

Form Approved
OMB No. 9000-0095
Expires July 31, 1995

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1a. NAME OF CONTRACTOR / SUBCONTRACTOR Physical Optics Corporation	**c. CONTRACT NUMBER** N00014-95-C-2011	**2a. NAME OF GOVERNMENT PRIME CONTRACTOR** N/A	**c. CONTRACT NUMBER**	**3. TYPE OF REPORT** *(X one)* a. INTERIM ☒ b. FINAL ☐
b. ADDRESS *(Include ZIP Code)* 20600 Gramercy Place Torrance, CA 90501	**d. AWARD DATE (YYMMDD)** 941108	**b. ADDRESS** *(Include ZIP Code)*	**d. AWARD DATE (YYMMDD)**	**4. REPORTING PERIOD (YYMMDD)** a. FROM 941108 b. TO 950808

SECTION I – SUBJECT INVENTIONS

5. "SUBJECT INVENTIONS" REQUIRED TO BE REPORTED BY CONTRACTOR / SUBCONTRACTOR *(If "None," so state)*

NAME(S) OF INVENTOR(S) *(Last, First, MI)* a.	TITLE OF INVENTION(S) b.	DISCLOSURE NUMBER, PATENT APPLICATION SERIAL NUMBER OR PATENT NUMBER c.	ELECTION TO FILE PATENT APPLICATIONS d. (1) UNITED STATES (a) YES	(b) NO	(2) FOREIGN (a) YES	(b) NO	CONFIRMATORY INSTRUMENT OR ASSIGNMENT FORWARDED TO CONTRACTING OFFICER e. (1) YES	(2) NO
None.								

f. EMPLOYER OF INVENTOR(S) NOT EMPLOYED BY CONTRACTOR / SUBCONTRACTOR

(1) (a) NAME OF INVENTOR *(Last, First, MI)* None.	(2) (a) NAME OF INVENTOR *(Last, First, MI)*
(b) NAME OF EMPLOYER	(b) NAME OF EMPLOYER
(c) ADDRESS OF EMPLOYER *(Include ZIP Code)*	(c) ADDRESS OF EMPLOYER *(Include ZIP Code)*

g. ELECTED FOREIGN COUNTRIES IN WHICH A PATENT APPLICATION WILL BE FILED

(1) TITLE OF INVENTION	(2) FOREIGN COUNTRIES OF PATENT APPLICATION

SECTION II – SUBCONTRACTS (Containing a "Patent Rights" clause)

6. SUBCONTRACTS AWARDED BY CONTRACTOR / SUBCONTRACTOR *(If "None," so state)*

NAME OF SUBCONTRACTOR(S) a.	ADDRESS *(Include ZIP Code)* b.	SUBCONTRACT NUMBER(S) c.	DFAR "PATENT RIGHTS" d. (1) CLAUSE NUMBER	(2) DATE (YYMM)	DESCRIPTION OF WORK TO BE PERFORMED UNDER SUBCONTRACT(S) e.	f. SUBCONTRACT DATES (YYMMDD) (1) AWARD	(2) ESTIMATED COMPLETION
None.							

SECTION III – CERTIFICATION

7. CERTIFICATION OF REPORT BY CONTRACTOR / SUBCONTRACTOR *(Not required if* ☒ *Small Business or* ☐ *Non-Profit organization.) (X appropriate box)*

a. NAME OF AUTHORIZED CONTRACTOR / SUBCONTRACTOR OFFICIAL (Last, First, MI) Tu, Olivia	**c.** I certify that the reporting party has procedures for prompt identification and timely disclosure of "Subject Inventions," that such procedures have been followed and that all "Subject Inventions" have been reported.	
b. TITLE Legal & Contracts Administrator	**d. SIGNATURE**	**e. DATE SIGNED** 960105

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PREVIOUS EDITION IS OBSOLETE.

EXECUTIVE SUMMARY

This is the final report for the U. S. Navy Contract, No. N00014-95-C-2011, entitled "Extremely Narrowband Cascaded Holographic Adjustable Range Tunable (ENCHART) Filter." The initial period of performance was from 11/08/94 to 05/08/95. This was extended three months to 08/08/95 for the performance of Option Task 7. This Phase I SBIR project successfully demonstrated a technology enabling extremely narrow band tunable filters based on cascaded Fabry-Perot interferometers with holographic mirrors and liquid crystal tuning elements.

1.0 INTRODUCTION

The use of tunable narrowband optical filters is critical for many advanced systems. For example, optical sensors are used in solar and terrestrial observatories, laboratory diagnostics, and other spectrometry applications. These systems require tunable optical filters with a bandwidth on the order of a tenth of an Angstrom operating over the full optical range (from UV to IR), with high out-of-band rejection. In addition, these filters must be relatively small, lightweight, and sturdy, and constructed of materials that can withstand long exposure to the space environment.

In the course of this Phase I project, Physical Optics Corporation's R&D Division (POC) designed and developed a new Extremely Narrowband Cascaded Holographic Adjustable Range Tunable (ENCHART) filter using two holographic Fabry-Perot filters (HFPFs): a coarse filter to select the desired portion of the optical range, and an extremely narrow (0.1 Å) bandwidth fine filter operating within this selected range at any arbitrary wavelength. The fine filter was an electrically tuned liquid-crystal cell.

Three existing POC techniques were applied to the ENCHART filter design and prototype fabrication. These are illustrated in Figure 1-1:

- Coherently coupled HFPF recording
- High order, controlled bandwidth, harmonic holographic mirror recording
- Tunable liquid crystal cell preparation.

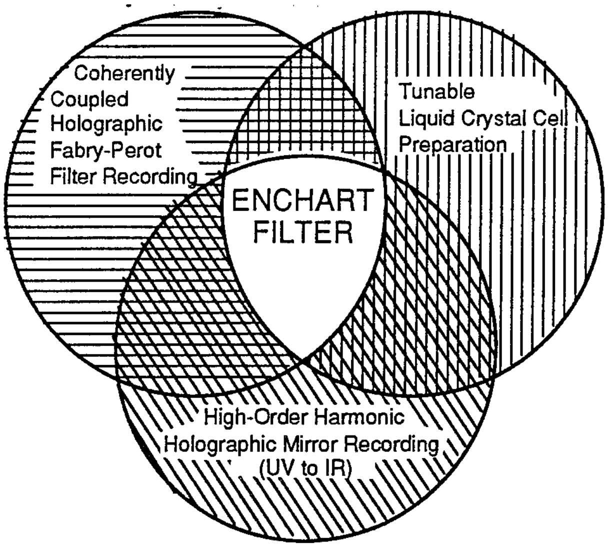


Figure 1-1
Three existing POC technologies combine to produce the Extremely Narrowband Cascaded Holographic Adjustable Tunable (ENCHART) filter design.

The following objectives were established for the Phase I project:

Objective 1. Design the proposed cascaded holographic Fabry-Perot filter to demonstrate a concept which is feasible within currently available technologies; determine design parameters.

Objective 2. Experimentally demonstrate the basic functions of the proposed filter by emphasizing:

- external coating for the liquid crystal cell holographic mirrors in the fine tunable filter
- high order harmonic technology using externally coated holographic mirrors that operate in the UV, visible, and IR range
- holographic notch filter processing technology for controlled narrow bandwidth Lippmann mirror HFPF applications, and
- cascaded filter approach.

Objective 3. Fabricate a proof-of-concept filter by integrating all component technologies and evaluating their performance. (Performance goals: pass bandwidth of 0.1 to 0.2 Å, range of operation between 600 and 700 nm, tunability of ±1 Å around the central wavelength, peak transmission at least 10%, out-of-band rejection OD = 2.0.)

In addition, the objective of the option task was to extend the technology into the violet-blue region of the spectrum.

As documented below in Sections 2.0 through 7.0, POC met or exceeded all these objectives.

The Phase I effort consisted of seven tasks: 1) ENCHART Filter Design; 2) Coating Technology Development; 3) High-Order Harmonic Recording; 4) Process Optimization; 5) Proof-of-Concept Red Filter Demonstration; 6) Final Report and 7) Proof-of-Concept Violet-Blue Filter Demonstration. The results obtained during the execution of Tasks 1 through 5 and (Option) Task 7 will now be described in detail.

2.0 ENCHART FILTER DESIGN

The cross section of the ENCHART filter as designed is shown in Figure 2-1. Figure 2-2 illustrates the operation of the ENCHART filter.

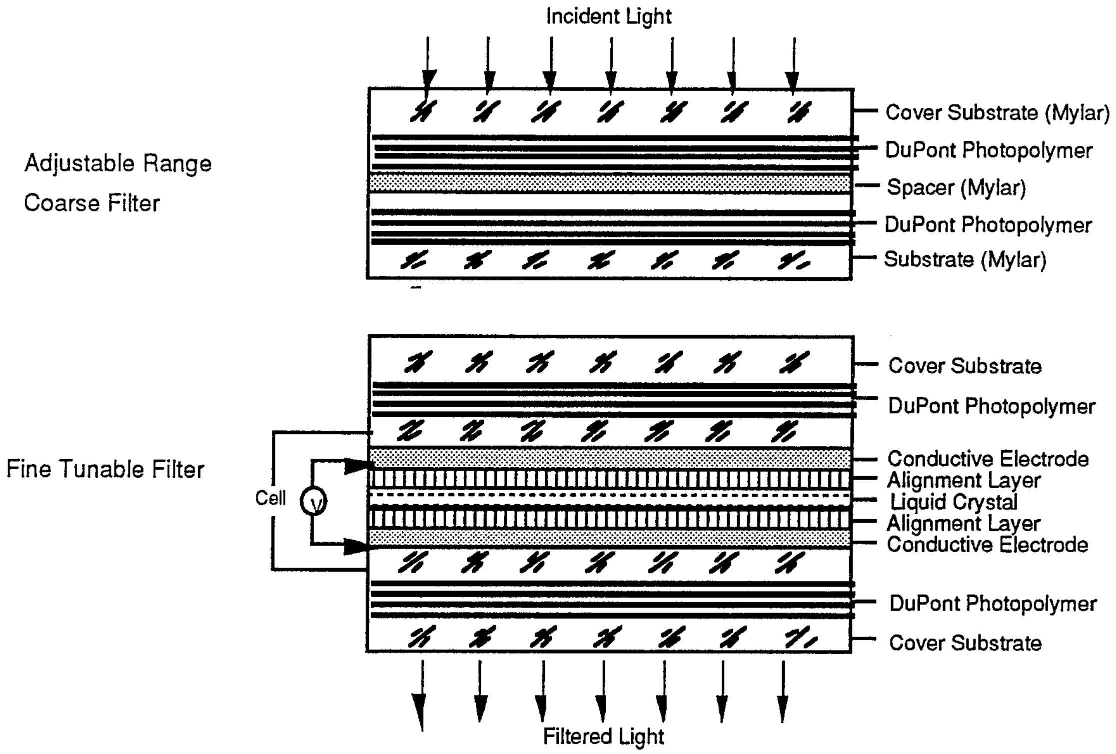


Figure 2-1
ENCHART filter design.

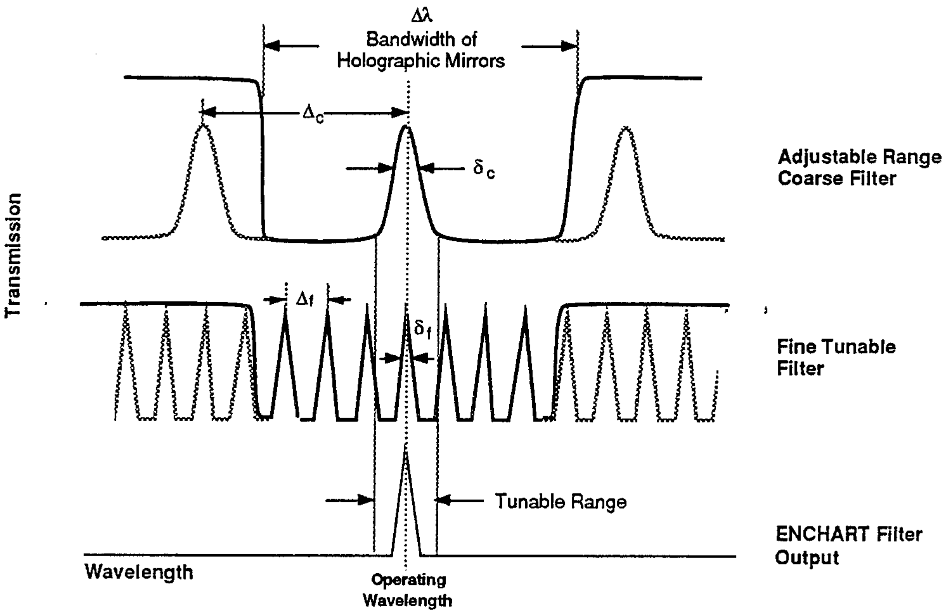


Figure 2-2
ENCHART filter operation.

The ENCHART filter design parameters are:

- **Coarse Filter:**
  - Free spectral range: $\Delta_c \geq 3$ nm
  - Finesse: $F_c > 20$
  - Full width at half maximum (FWHM): $\delta_c \leq 1.5$ Å
  - Bandwidth of the holographic mirrors: $\Delta\lambda < 6$ nm
- **Fine Tunable Filter:**
  - Free spectral range: $\Delta_f \geq 1.5$Å
  - Finesse: $F_f > 15$
  - FWHM: $\delta_f < 0.1$Å
  - Tunability range: $\Delta\lambda_T \geq 3$Å

These parameters reflect currently available technologies. The liquid crystal cell was coated with an external photopolymer coating.

3.0 CELL COATING TECHNOLOGY

A technology for coating the exterior of the liquid crystal cell with photopolymer was developed. This technology consists of two steps: preparing the liquid crystal cell using conventional technology and casting photopolymer onto the assembled cell.

DuPont photopolymer film HRF-352 was used in this application. The recording geometry is shown in Figure 3-1 and the recording setup in Figure 3-2.

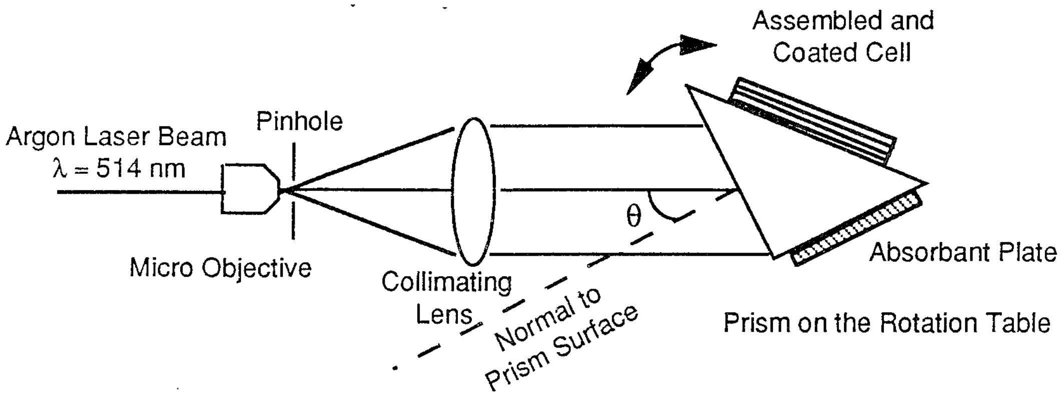


Figure 3-1
Geometry for holographic recording.

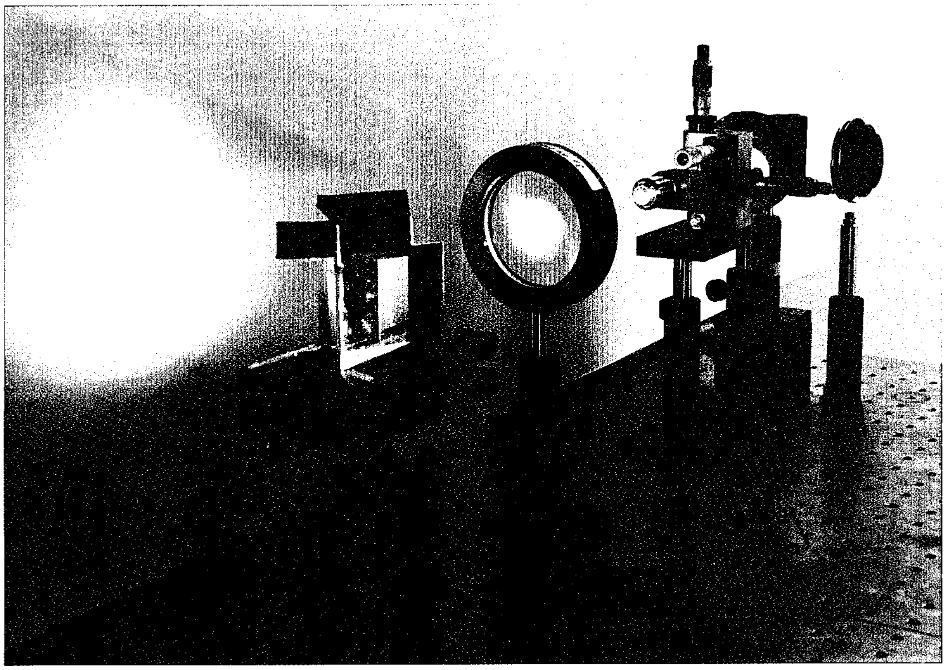


Figure 3-2
Experimental setup for recording the holographic filter using a 514 nm argon laser.

Plots of the performance of the HRF-352 DuPont photopolymer film are shown in Figure 3-3. The holographic mirrors were recorded using a 514 nm argon laser in a prism setup (θ = 16°) for exposures of 20 mJ, 40 mJ, 60 mJ, 80 mJ, and 100 mJ. Processing included a 60 second UV cure and a two hour bake at 115°C.

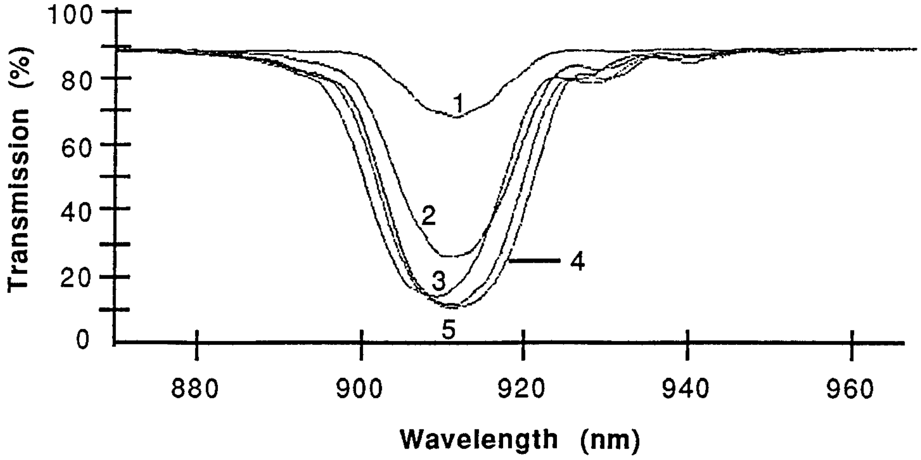


Figure 3-3
Transmission vs. wavelength for HRF-352 DuPont photopolymer film for exposures of (1) 20 mJ, (2) 40 mJ, (3) 60 mJ, (4) 80 mJ, and (5) 100 mJ.

4.0 HIGHER ORDER HARMONIC RECORDING

The technology to record high-order harmonics in the DuPont photopolymer exterior coating of the cell was investigated and developed in this Phase I effort. The experimental data is summarized in Figures 4-1 and 4-2 and Tables 4-1 and 4-2.

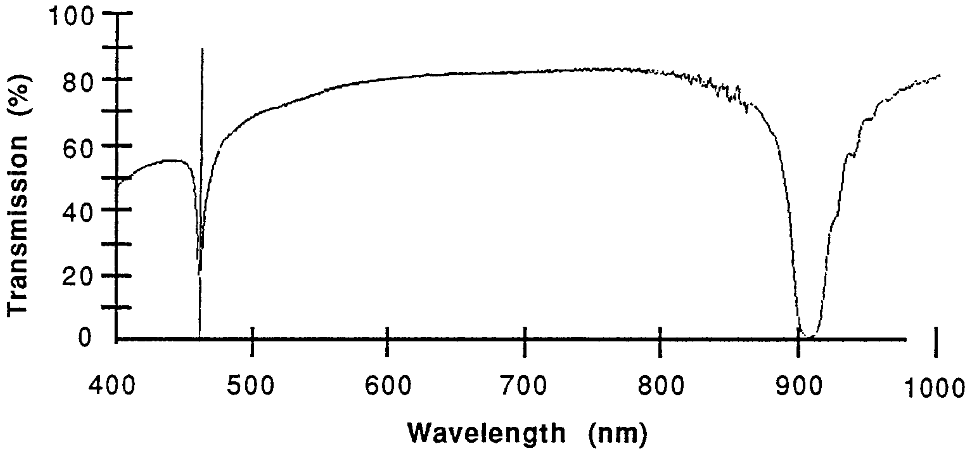


Figure 4-1
Holographic mirror at a primary wavelength of 920 nm and a second harmonic of 460 nm. Recorded using a prism setup. Exposure was made on HRF-352 DuPont photopolymer film at θ = 16° with an argon laser, λ = 514 nm.

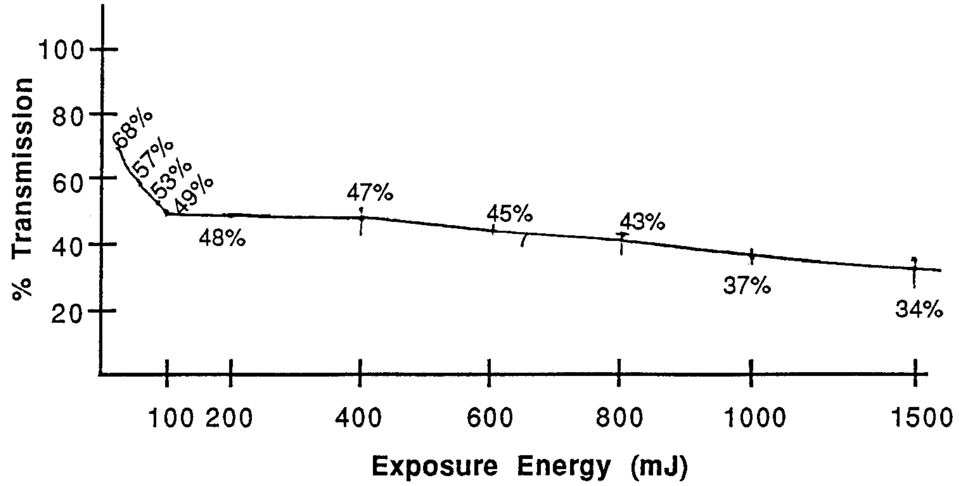


Figure 4-2
Transmission vs. exposure energy for a second harmonic holographic mirror recorded on DuPont HRF-352 using a prism setup. Illumination angle θ = 16°, argon laser at 514 nm, beam intensity 4 mW/cm^2.

Table 4-1 Performance of Second Harmonic Holographic Mirror as a Function of Exposure and Processing

No.	θ (deg)	Exp (mJ)	115°C Peak λ (nm)	60 hr Bake % Transmittance	115°C Peak λ (nm)	72 hr Bake % Transmittance
1	16	1000	442.4	14.8	443.2	14.7
2	16	2000	442.2	18.8	442.8	14.8
3	16	3000	441.6	14.9	442.0	15.1
4	16	4000	443.0	13.8	443.8	14.1
5	16	5000	443.4	17.6	444.0	17.2

Table 4-2 Holographic Mirror Spectral Adjustment as a Function of Prism Recording Geometry and Processing

	Peak Wavelength, λ_0 (nm)			
No.	Angle of Incidence, θ (deg)	Before Bake	12 hr Bake	24 hr Bake
1	5	387.2	384.8	383.0
2	10	414.0	411.6	411.0
3	15	444.8	442.0	443.0
4	20	483.0	481.2	481.8
5	25	523.2	520.2	520.8
6	30	---	583.6	584.0
7	35	---	644.4	645.2
8	40	---	739.8	739.4

Note: All samples were exposed at 1000 mJ.

5.0 PROCESS OPTIMIZATION

The technology for recording photopolymer holographic notch filters was modified to control the mirror's characteristics. Table 5-1 summarizes the experimental data.

Table 5-1 Playback Wavelength and Transmittance as a Function of Processing

Processing Step	Playback Wavelength λ (nm)		% Transmittance at Playback Wavelength	
	Sample 1	Sample 2	Sample 1	Sample 2
Overall UV cure, 90 sec.	467.8	467.6	72.8	74.7
Heat, 115°C 15 min.	465.2	465.4	72.5	70.9
30 min.	465.4	465.0	75.1	72.6
60 min.	464.6	465.2	77.9	75.6
12 hr	463.8	463.8	41.8	37.5
48 hr	463.4	462.6	29.0	27.1

Note: Sample 1 was exposed at 1000 mJ
Sample 2 was exposed at 200 mJ.

In order to obtain a single-peak instrumental profile with the adjustable range coarse filter (see Figure 2-2) the bandwidth $\Delta\lambda$ of the holographically recorded mirrors must be less than the free spectral range Δ_C of the adjustable range coarse filter, i.e., $\Delta\lambda < \Delta_C$.

A plot of the instrumental profile (transmission vs. wavelength) of an adjustable range coarse filter with single-peak transmission is shown in Figure 5-1. This filter was recorded on DuPont photopolymer.

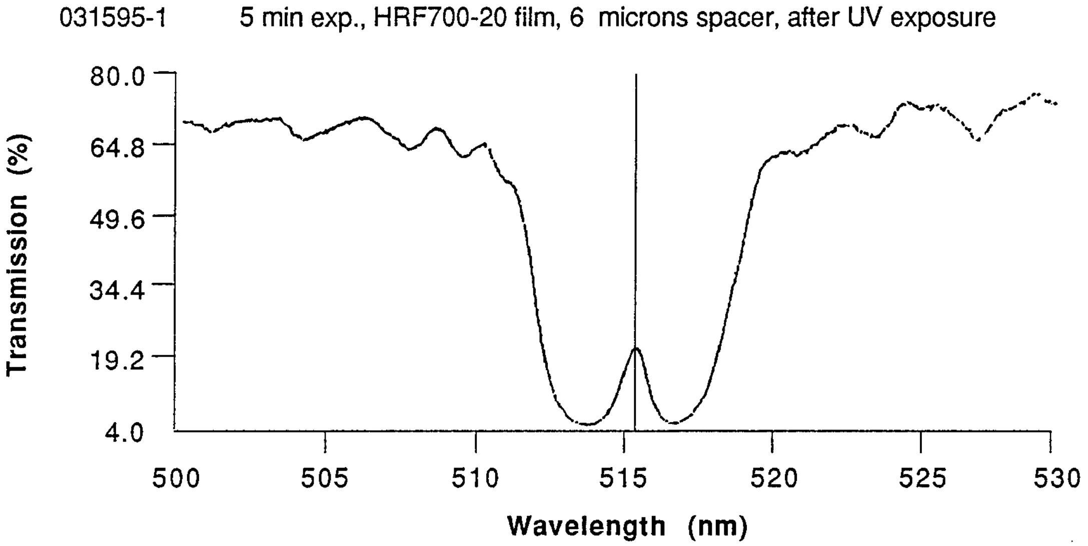


Figure 5-1
Transmission vs. wavelength of an adjustable range coarse filter with a single transmission peak across the holographic mirror bandwidth of 7 nm (8% Fresnel correction should be added to the transmission peak value).

Figure 5-2 shows the single Fabry-Perot fringe corresponding to the single transmission peak.

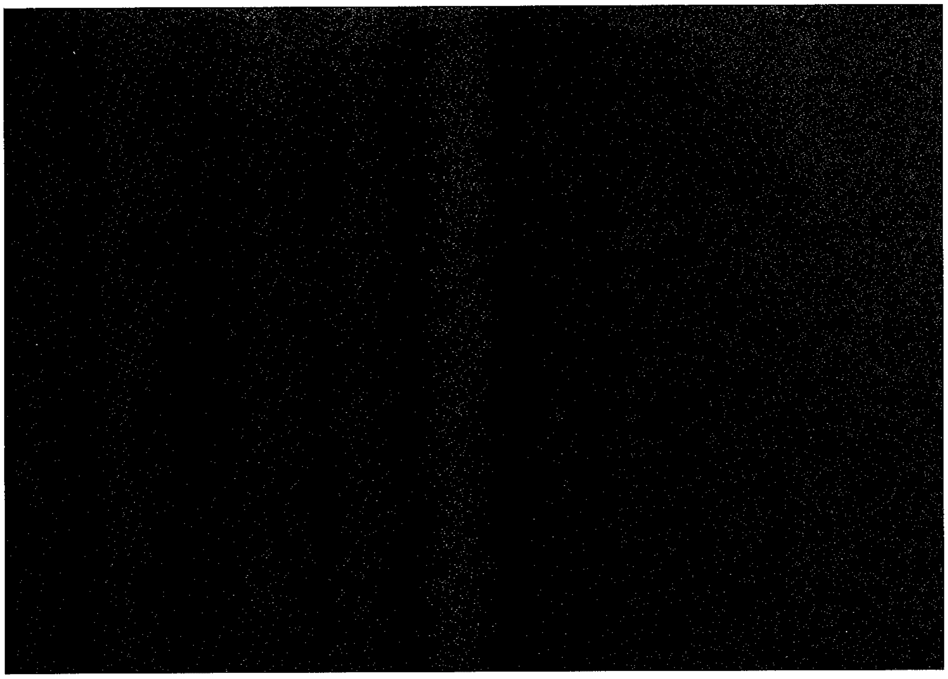


Figure 5-2
Single Fabry-Perot fringe, corresponding to the single transmission peak shown in Figure 5-1.

6.0 PROOF-OF-CONCEPT RED FILTER

To demonstrate the feasibility of the proposed approach, holographic adjustable range coarse filters (ARCFs) in the infrared, red, green, and violet ranges of the optical spectrum were recorded using the prism setup, an argon laser ($\lambda = 514$ nm) as the light source, and HRF-352 DuPont photopolymer film as the recording medium. Experimental results are summarized in Figures 6-1 through 6-4.

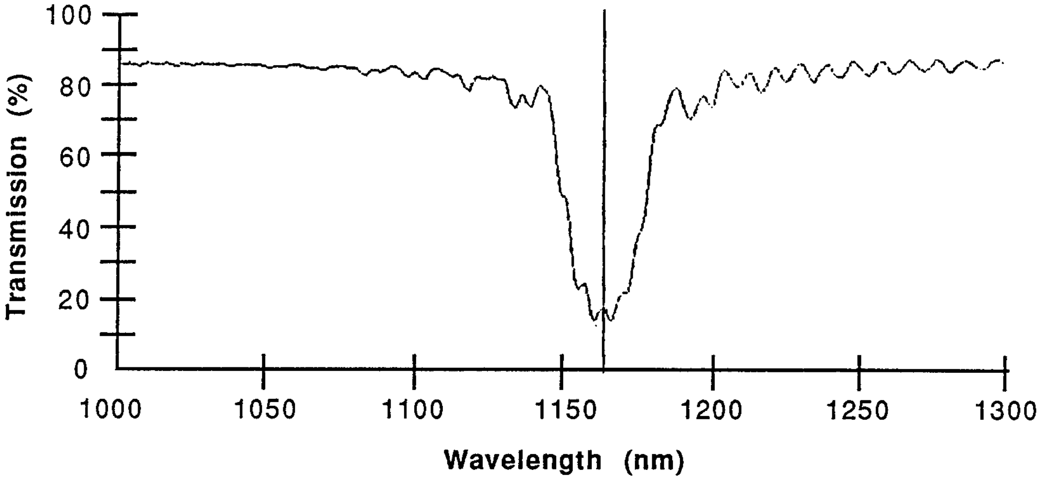
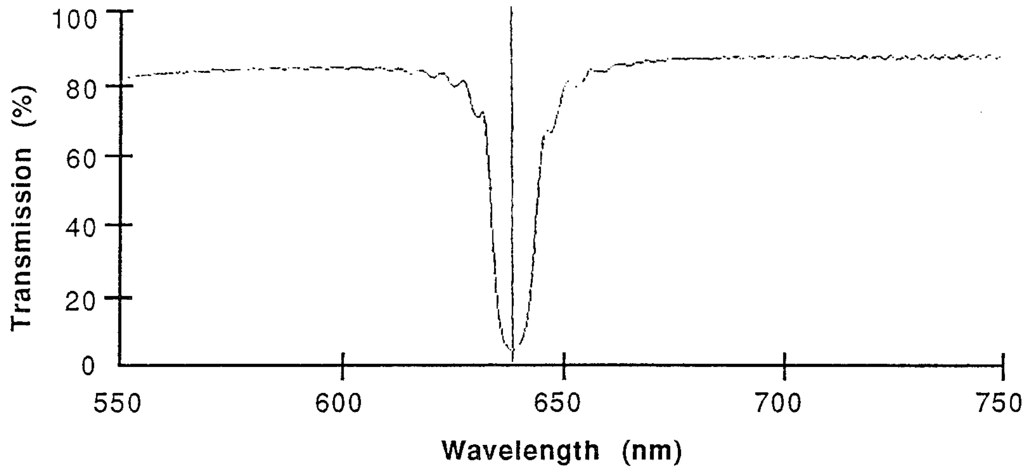
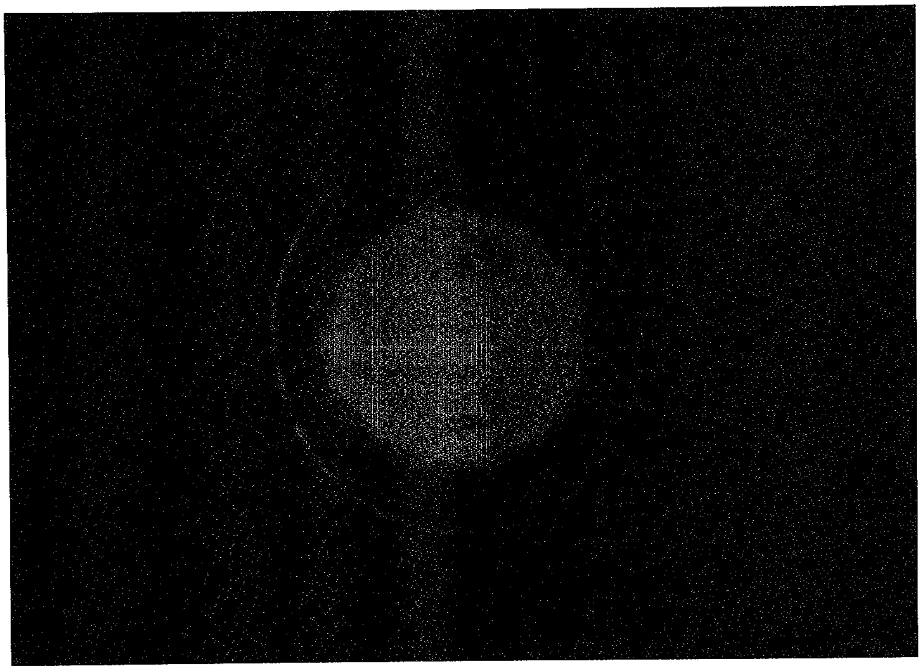


Figure 6-1
Transmission vs. wavelength of coarse filter adjusted to work in the near infrared (1164 nm). Recorded at 514 nm, primary harmonic.

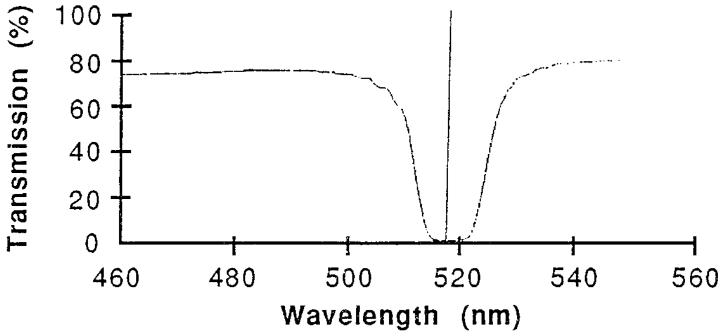


(a) Transmission vs. wavelength.

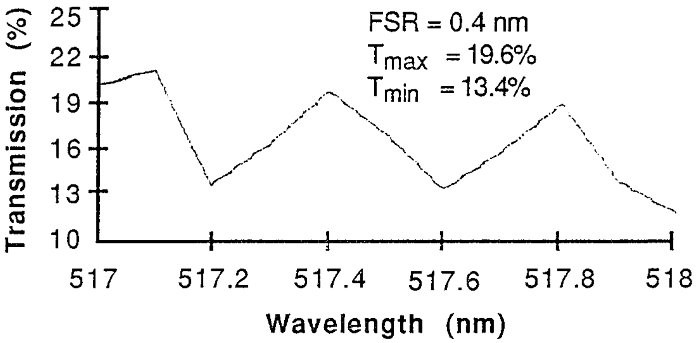


(b) Fabry-Perot rings on the screen. Measured FSR = 14 Å, estimated finesse is approximately 20; resolution is 0.7 Å.

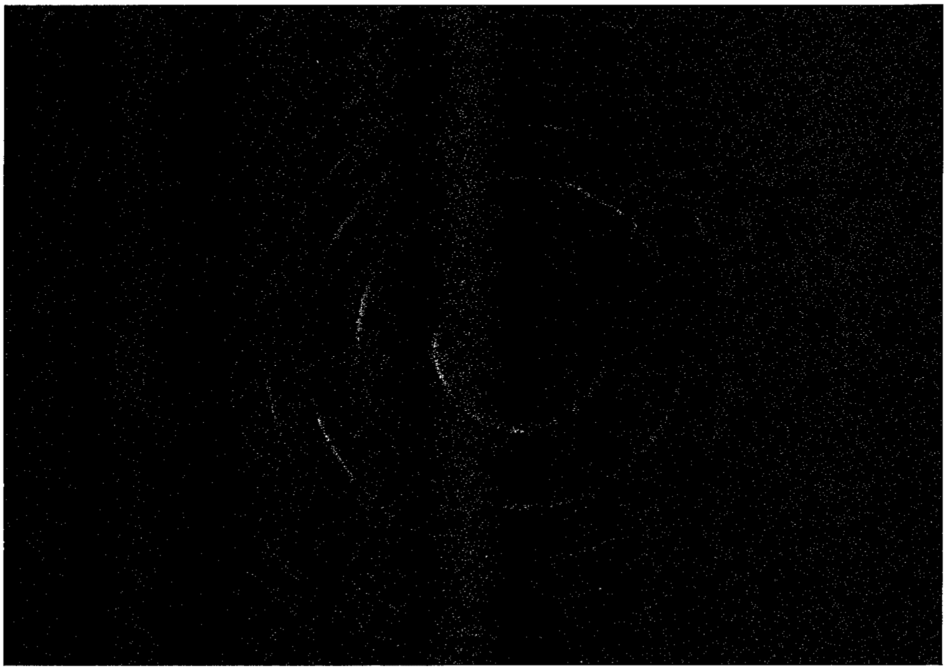
Figure 6-2
Coarse filter adjusted to the red range (639.6 nm) of the spectrum.
Recorded at 514 nm, primary harmonic.



(a) Transmission vs. wavelength.

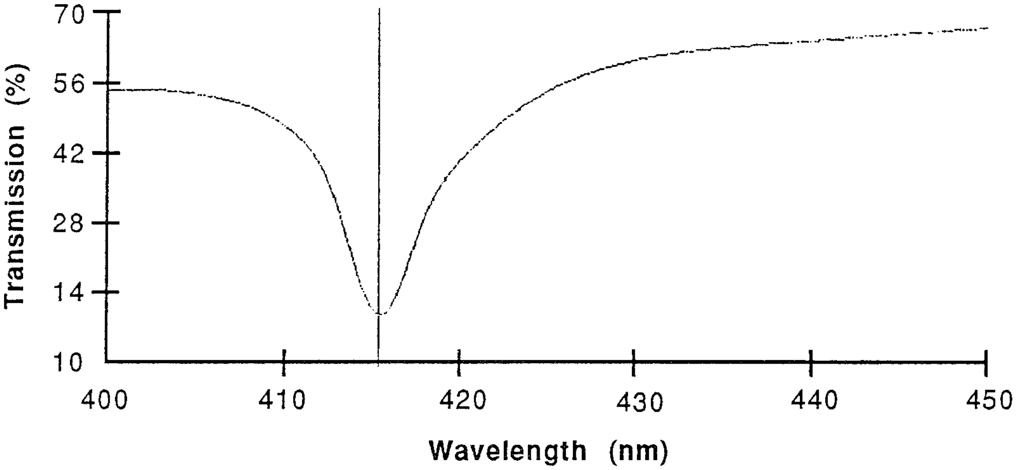


(b) Transmission vs. wavelength.

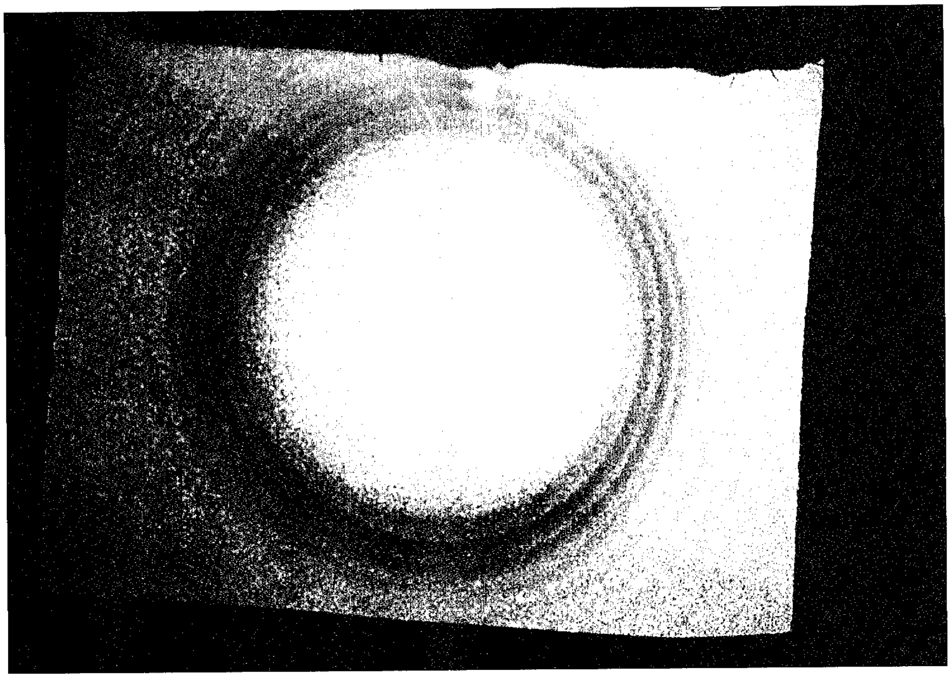


(c) Fabry-Perot rings on the screen. Measured FSR = 4 Å, estimated finesse is approximately 10; resolution is 0.4 Å.

Figure 6-3
Extremely narrowband coarse filter adjusted to the green (520 nm) range of the spectrum.
Recorded at 514 nm, primary harmonic.



(a) Transmission vs. wavelength in the blue-violet range.



(b) Fabry-Perot rings on the screen. Estimated finesse on the order of 5 causes high losses in the material in the blue-violet range.

Figure 6-4
Coarse filter adjusted to the blue-violet range (415 nm) of the spectrum.
Recorded at 514 nm, secondary harmonic.

Two methods were used to measure ENCHART filter parameters: instrumental measurement using a spectrophotometer, and physical measurement based on an optical setup. Neither is complete because of the limited resolution of the spectrophotometers and the difficulty of obtaining highly accurate measurements with the optical setup. Nevertheless, these methods are acceptable for determining basic parameters. A Perkin Elmer Lambda-9 spectrophotometer was used for measuring ENCHART filter parameters. Unfortunately, even in its highest resolution mode, this device is limited by its imperfect beam collimation. Figure 6-5 shows the instrumental profile (transmission vs. wavelength) of the fine holographic filter operating at 514 nm.

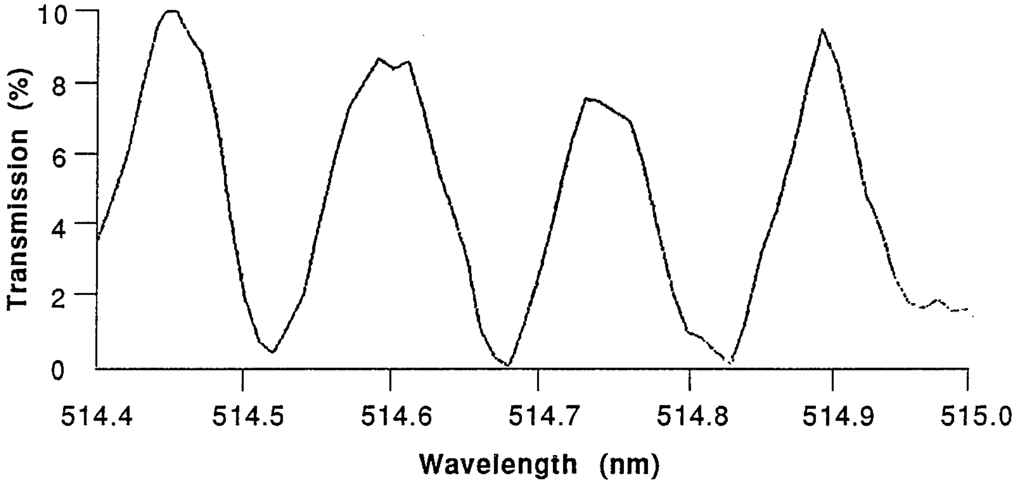


Figure 6-5
Transmission vs. wavelength of the fine holographic filter operating at 514 nm. (8% Fresnel correction should be added to the transmission peak value.)

It can be seen from Figure 6-5 that the free spectral range (FSR) $\Delta = 1.5$ Å, and the full width at half maximum (FWHM), which determines the filter's resolution, is $\delta \approx 0.7$ nm. The physical measurement, presented in Figure 6-6, demonstrated an actual resolution for the same samples of

$$\delta = \Delta/F = 1.5\ \text{Å}/15 \approx 0.1\ \text{Å}\ . \qquad (6\text{-}1)$$

The estimated value of finesse F = 15 was based on the measurement of the ratio Δ/δ from the photo in Figure 6-6.

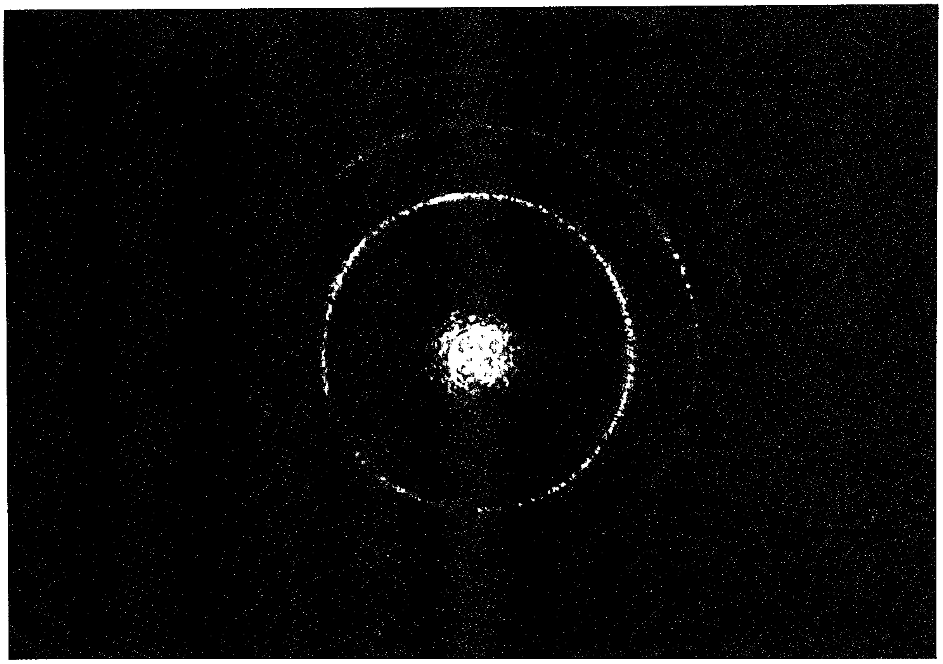


Figure 6-6
Fabry-Perot fringes of the same fine holographic filter used to generate the data plotted in Figure 6-5. The FSR (distance between rings) is around 15 times greater than the FWHM (thickness of a ring). Thus the actual resolution is 0.1 Å.

For an etalon with a tunable spacer, the overall etalon phase change, $\Delta\phi$, is (for normal incidence):

$$\Delta\phi=(4\pi/\lambda)d\cdot\Delta n \qquad (6\text{-}2)$$

where d is the spacer thickness, Δn is the index change, and λ is the optical wavelength. The distance between etalon maxima is determined by $\Delta(\Delta\phi) = 2\pi$; thus,

$$\Delta n = (\lambda/2d)\ . \qquad (6\text{-}3)$$

The refractive index change Δn can be expressed in terms of the electro-optic (EO) coefficient α_{EO} as $\Delta n = \alpha_{EO} \bullet E$, where the electrical field E can be written in terms of voltage as $E = V/d$.

Therefore, we obtain

$$V = (\lambda/2\alpha_{OE})\ . \qquad (6\text{-}4)$$

The EO coefficient value for $LiNbO_3$ and other ferroelectric crystals is too small (~100 pm/V) to achieve the required etalon tunability. By contrast, for nematic liquid crystals (LC) this coefficient is much higher, on the order of 0.2 μm/V. The required voltage is:

$$V = 0.5\ \mu m/(2 \times 0.2\ \mu m/V) = 1.25\ V \qquad (6\text{-}5)$$

for $\lambda = 0.5\ \mu m$.

The experimental evaluation of the ENCHART filter was initiated by measuring its voltage-dependent transmission characteristic. A schematic of the measurement setup is shown in Figure 6-7.

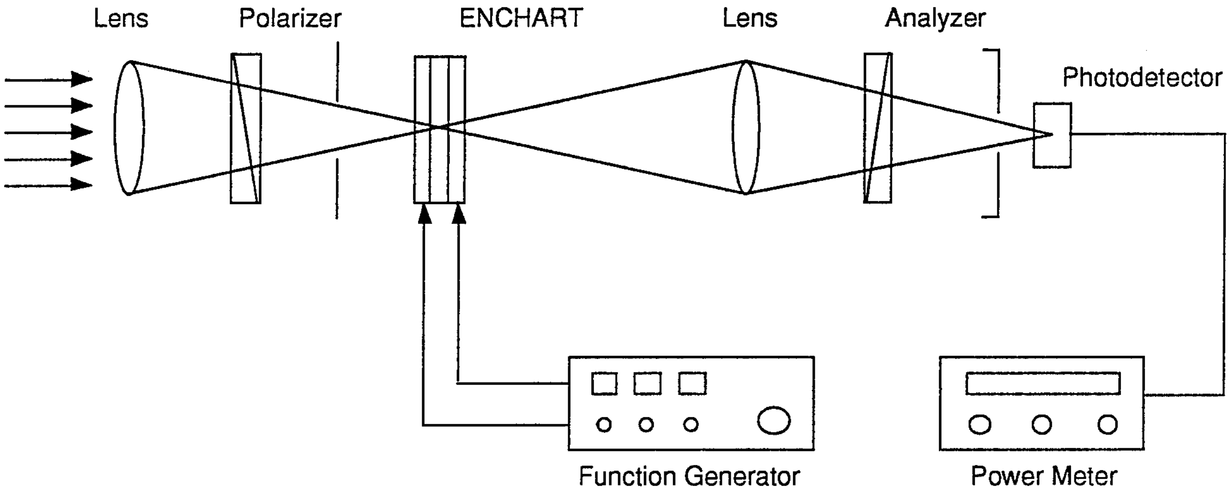


Figure 6-7
Experimental setup for measuring ENCHART characteristics.

The incident beam (from an Ar laser at $\lambda = 514$ nm) is focused to produce a 1 mm diameter spot on the ENCHART filter. Liquid crystal BDH E70 was used as the tunable medium in the ENCHART filter. The filter was driven with a 0.8 kHz square wave that was ramped from 0 V to 5 V, using a function generator. Transmitted light was collected and focused by a lens through an optical analyzer, onto a photodetector. The measured transmitted intensity I versus voltage is shown in Figure 6-8.

Figure 6-9 is a detail of Figure 6-8, illustrating the tunability of the ENCHART filter.

The photos in Figure 6-10 illustrate the Fabry-Perot fringes for four selected values of applied voltage: 0.5 V, 1 V, 1.5 V, and 2 V.

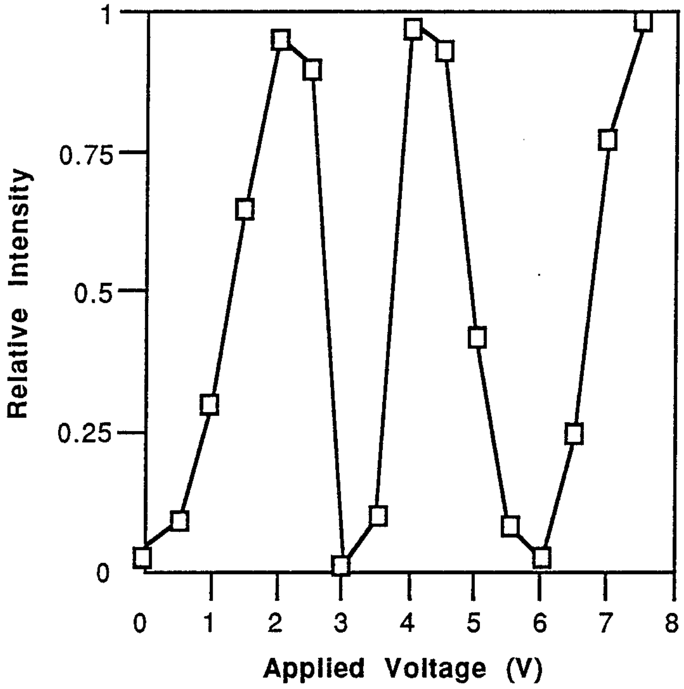


Figure 6-8
Measured transmitted intensity of the ENCHART filter vs. voltage.

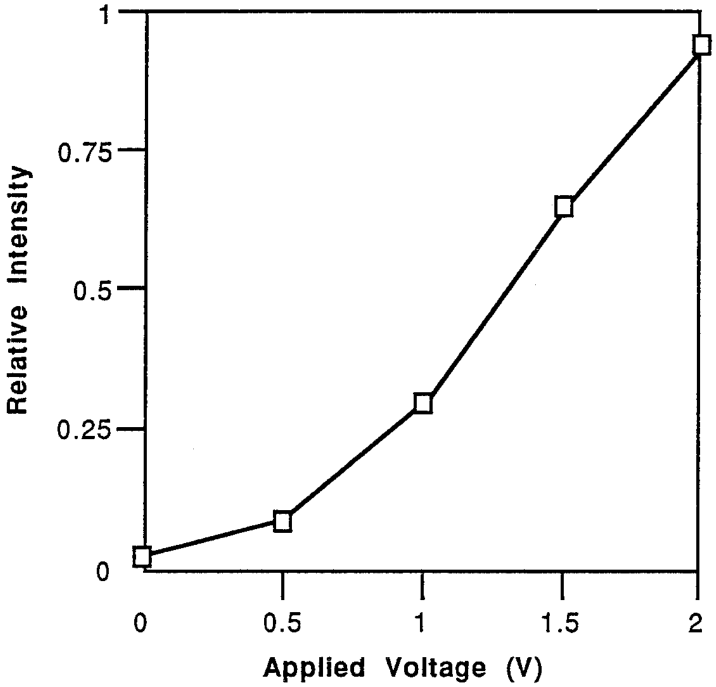


Figure 6-9
Detail of the transmitted intensity vs. applied voltage curve shown in Figure 6-8.

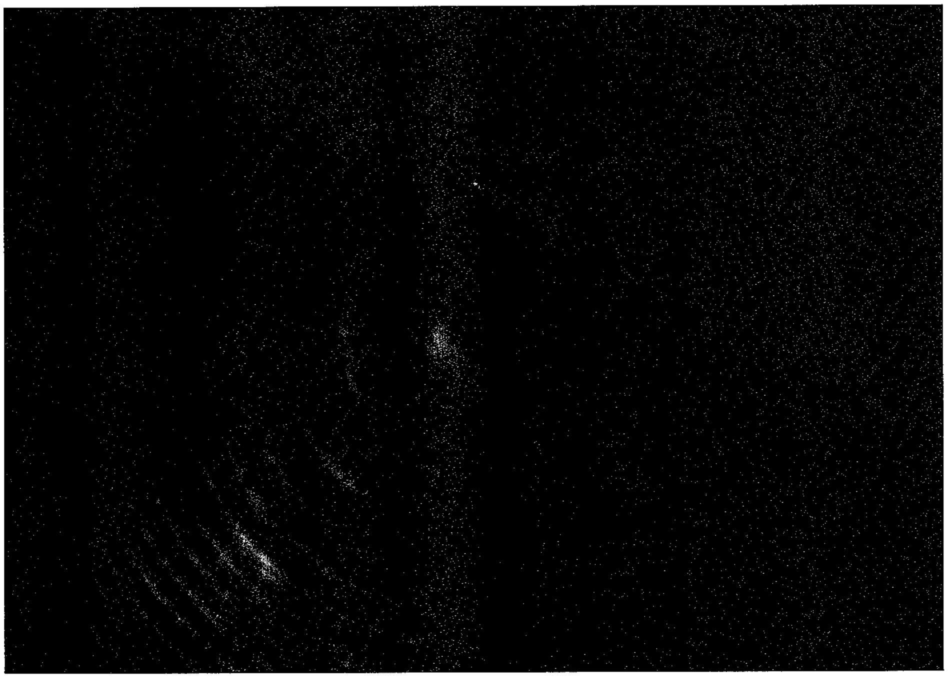


Figure 6-10 (a) 0.5 V

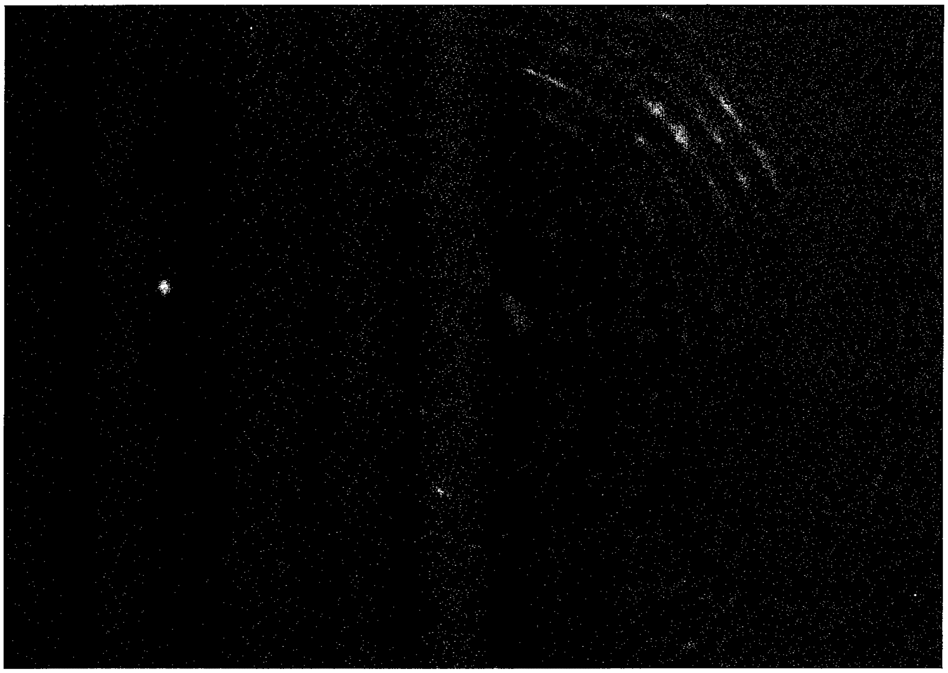


Figure 6-10 (b) 1.0 V

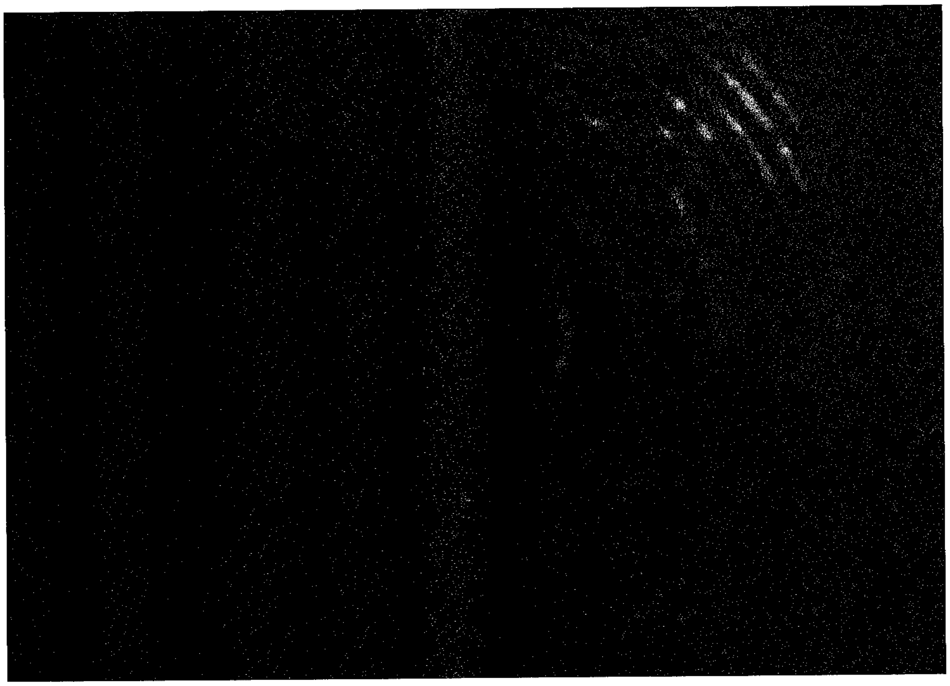


Figure 6-10 (c) 1.5 V

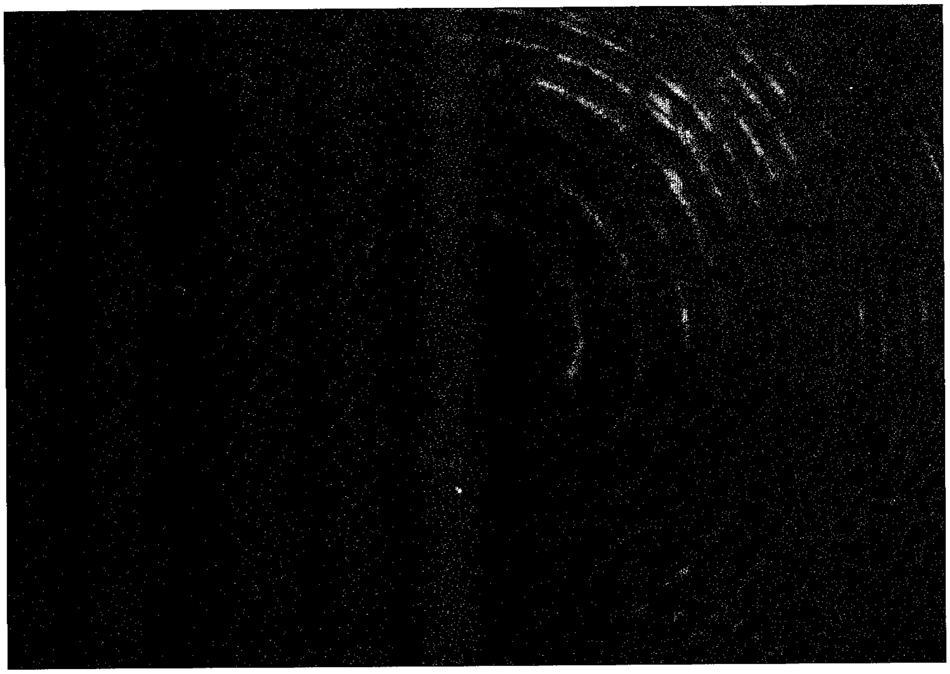


Figure 6-10 (d) 2.0 V

Figure 6-10
Experimental demonstration of the tunability of the fine tunable holographic filter. Holographic coherently coupled mirrors were recorded on a liquid crystal cell coated with DuPont photopolymer film. Fabry-Perot fringes at four voltages ((a) 0.5 V, (b) 1.0 V, (c) 1.5 V, and (d) 2.0 V) were applied to the liquid crystal cell. The phase of the trace in (a) differs by π from the phase in (d).

7.0 PROOF OF CONCEPT BLUE FILTER

Using the high order harmonic technique, the coherently coupled Fabry-Perot etalon was recorded on DuPont photopolymer on the external surfaces of the liquid crystal cell. The results of tuning the filter are shown in Figure 7-1, and the transmitted intensity vs. applied voltage is plotted in Figure 7-2.

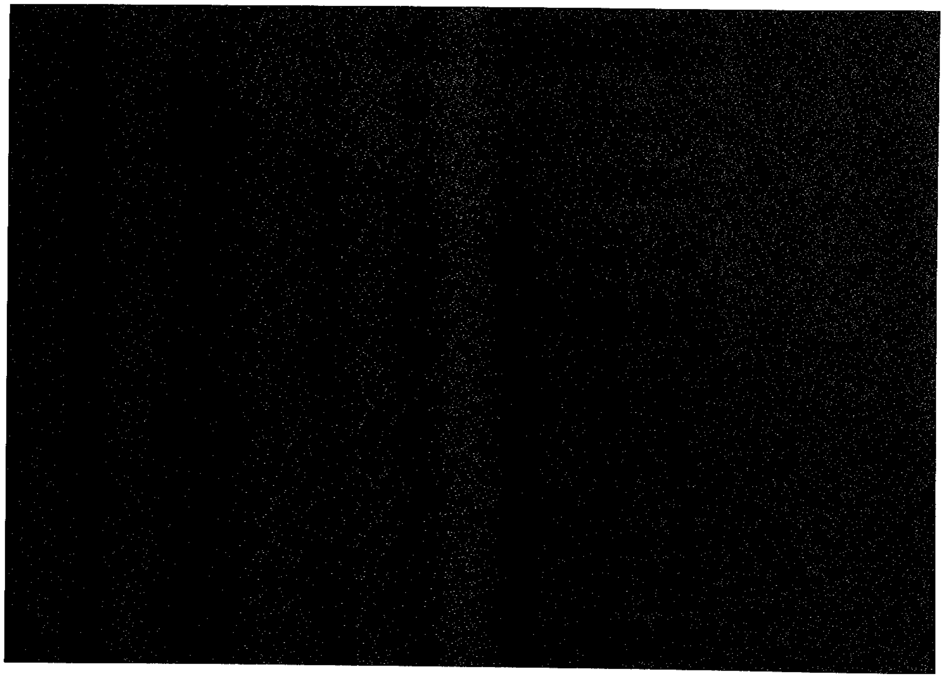


Figure 7-1(a) 6.5 V.

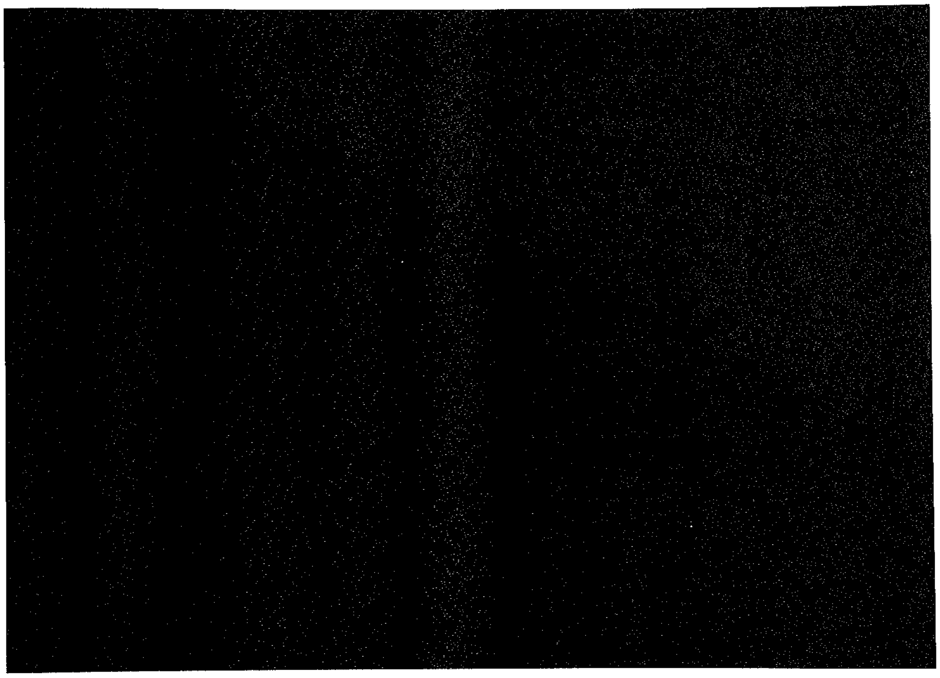


Figure 7-1(b) 7 V.

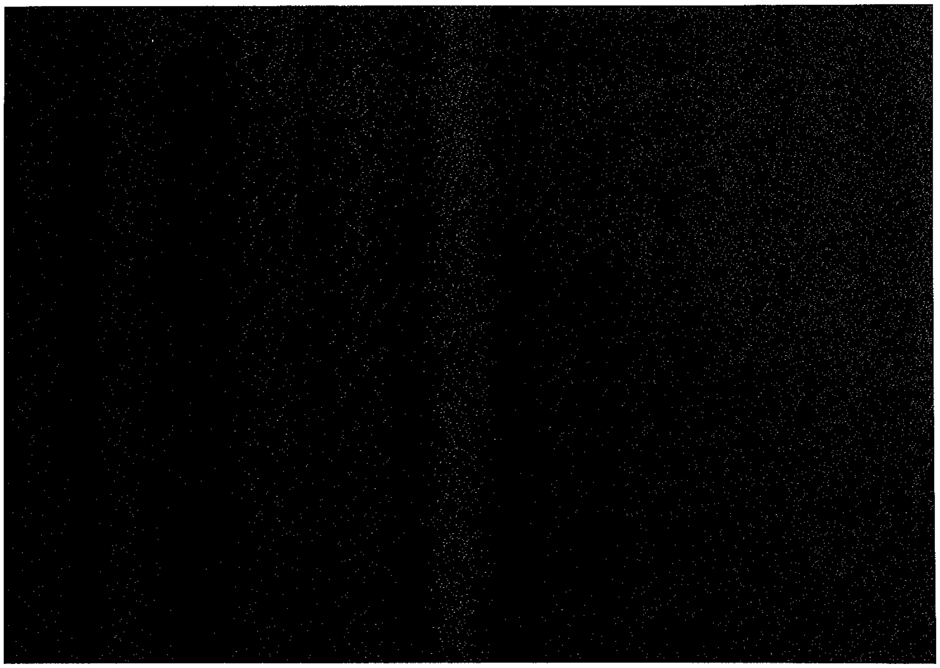


Figure 7-1(c) 7.5 V.

Figure 7-1
Experimental demonstration of the tunability of the fine tunable holographic filter in the blue spectral range. Fabry-Perot fringes at three voltages: (a) 6.5 V, (b) 7 V, and (c) 7.5 V were applied to the liquid crystal cell. The phase in (a) differs by π from the phase in (c).

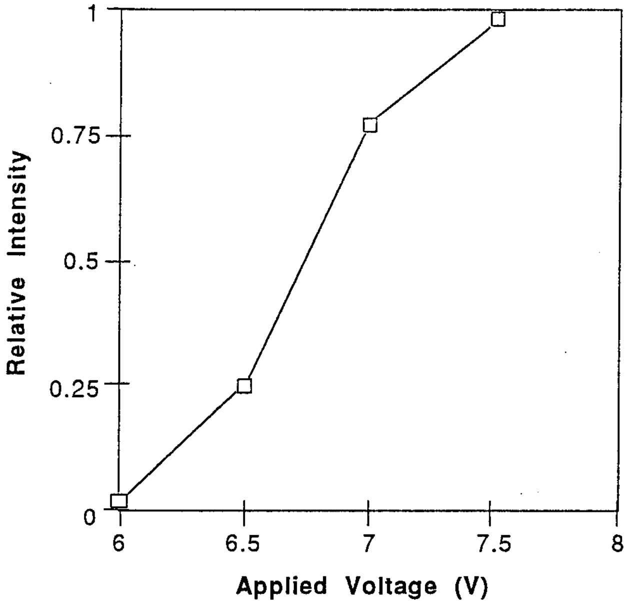


Figure 7-2
Transmitted intensity vs. applied voltage for fine tunable holographic filter operating at 413 nm.

8.0 CONCLUSION

In Phase I, Physical Optics Corporation's R&D Division (POC) designed and developed a new Extremely Narrowband Cascaded Holographic Adjustable Range Tunable (ENCHART) filter using two holographic Fabry-Perot filters (HFPFs): a coarse filter to select the desired portion of the optical range, and an extremely narrow (0.1 Å) bandwidth fine filter operating within this selected range at any arbitrary wavelength. The fine filter is an electrically tuned liquid-crystal cell. All established objectives were exceeded and a proof-of-concept ENCHART prototype was fabricated. This technology was extended to and demonstrated in the violet-blue region of the spectrum.