OPTICAL EXCISION PROGRAM

OPTICAL EXCISION FINAL REPORT

PSI-ER-5538-05

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OPTICAL EXCISION PROGRAM

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EXECUTIVE SUMMARY

This report summarizes the results obtained by PROBE SYSTEMS as part of a joint DARPA/NAVELEX program for investigation of optical excision. As originally conceived, optical excision is an acousto-optic technique for adaptively rejecting narrowband interference from broadband signals. This adaptive rejection of narrowband interference is an important means of reducing the vulnerability of spread spectrum systems to narrowband jamming.

As the optical excisor program progressed, it was gradually realized that the optical excisor has considerable potential for a variety of applications in addition to narrowband frequency rejection. In general terms the optical excisor acts as a broadband, high-resolution linear filter which can be used for programmable or adaptive filtering of electronic signals. Laboratory experiments demonstrated that high Q, linear-phase filters comparable in performance to fixed SAW filters could be constructed with the additional benefits of real-time filter response control. Other laboratory experiments indicated that the optical excisor could achieve the high dynamic range, phase coherence, and frequency stability required for processing of modern broadband electronic signals.

The optical excisor program contained a large variety of important analytical and experimental results. Broadband tests were performed to compare architectures and evaluate components. A brassboard optical excisor was also constructed and field tested in a modern spread-spectrum intercept system. These experiments resulted in four separate technical reports in addition to this final report. Two other publications relevant to optical excision but separate from the optical excision contract were also generated by PROBE personnel.

A number of important topics regarding optical excisor applications and development requirements are discussed in this final report. Several optical excisor types, functions and generic systems applications are described. Past optical excisor performance measurements are compared to future performance goals. The required component development and systems integration work needed to attain these goals is outlined.

The Appendix of this final report contains new and encouraging data regarding the filter depth and signal dynamic range of an optical excisor. This data reveals impressive performance for an existing optical excisor and points the way for even more impressive performance with future optical excisors.

1.0 INTRODUCTION

This report summarizes the results obtained by PROBE SYSTEMS as part of a joint DARPA/NAVELEX program for investigation of "optical excision." As originally conceived, optical excision is an acousto-optic technique for adaptively rejecting narrowband interference from a broadband signal. This adaptive rejection of narrowband interference is an important means of reducing the vulnerability of spread-spectrum communication, radar, and intercept systems to narrowband jamming.

A number of important topics regarding optical excisor applications and development requirements are discussed in this final report. Several optical excisor types, functions and generic systems applications are described. Past optical excisor performance measurements are compared to future performance goals. The required component development and systems integration work needed to attain these goals is outlined.

The Appendix of this final report contains new and encouraging data regarding the filter depth and signal dynamic range of an optical excisor. This data reveals impressive performance for an existing optical excisor and points the way for even more impressive performance with future optical excisors.

2.0 OPTICAL EXCISOR TYPES

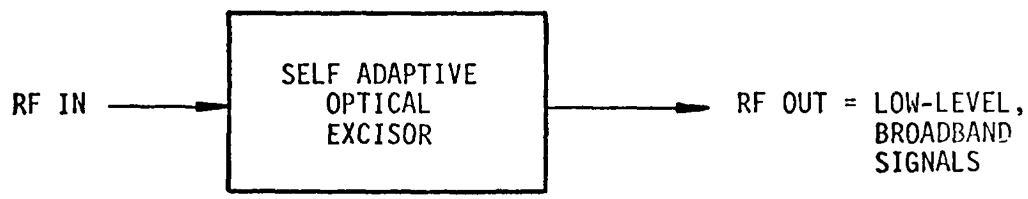
An optical excisor accepts an electronic RF input signal and produces one or two linearly-filtered, electronic RF outputs. The frequency response of the optical excisor may be self-adaptive in response to the power spectrum of the RF input, or the frequency response may be externally programmed. These basic distinctions lead to four fundamental optical excisor types:

1. Single-output, self-adaptive,
2. Dual-output, self-adaptive,
3. Single-output, programmable,
4. Dual-output, programmable.

The functional characteristics of the optical excisor types are described below.

The single-output, self-adaptive optical excisor is primarily intended for narrowband frequency rejection and received much of the attention of the optical excision program. The concept of the single-output, self-adaptive optical excisor is shown in Figure 2-1. The RF input contains both broadband and narrowband signals. The self-adaptive excisor senses the power spectrum of the RF input and attenuates the linear filter response of those frequency bands above a set threshold. As a result, the RF output of the self-adaptive excisor contains only the low-level, broadband portions of the RF input.

A model for the single-output, self-adaptive optical excisor is shown in Figure 2-2. The RF input is filtered by a bank of linear passband filters into N adjacent frequency channels. Each frequency channel is phase linear and the sum of adjacent frequency channels results in a wider passband filter response with essentially no filter gaps. The average power in each frequency channel is sensed and used to control the gain of that frequency channel. The frequency channels are then combined to produce the linear RF output of the optical excisor.



THE RF INPUT CONTAINS HIGH-LEVEL, NARROWBAND SIGNALS PLUS LOW-LEVEL, BROADBAND SIGNALS. THE OPTICAL EXCISOR ACTS AS A LINEAR FILTER WHOSE FREQUENCY RESPONSE ADAPTS TO REJECT THE HIGH-LEVEL, NARROBAND SIGNALS WHILE PASSING THE LOW-LEVEL, BROADBAND SIGNALS TO THE RF OUTPUT FOR USE BY WIDEBAND SIGNAL PROCESSORS AND RECEIVERS.

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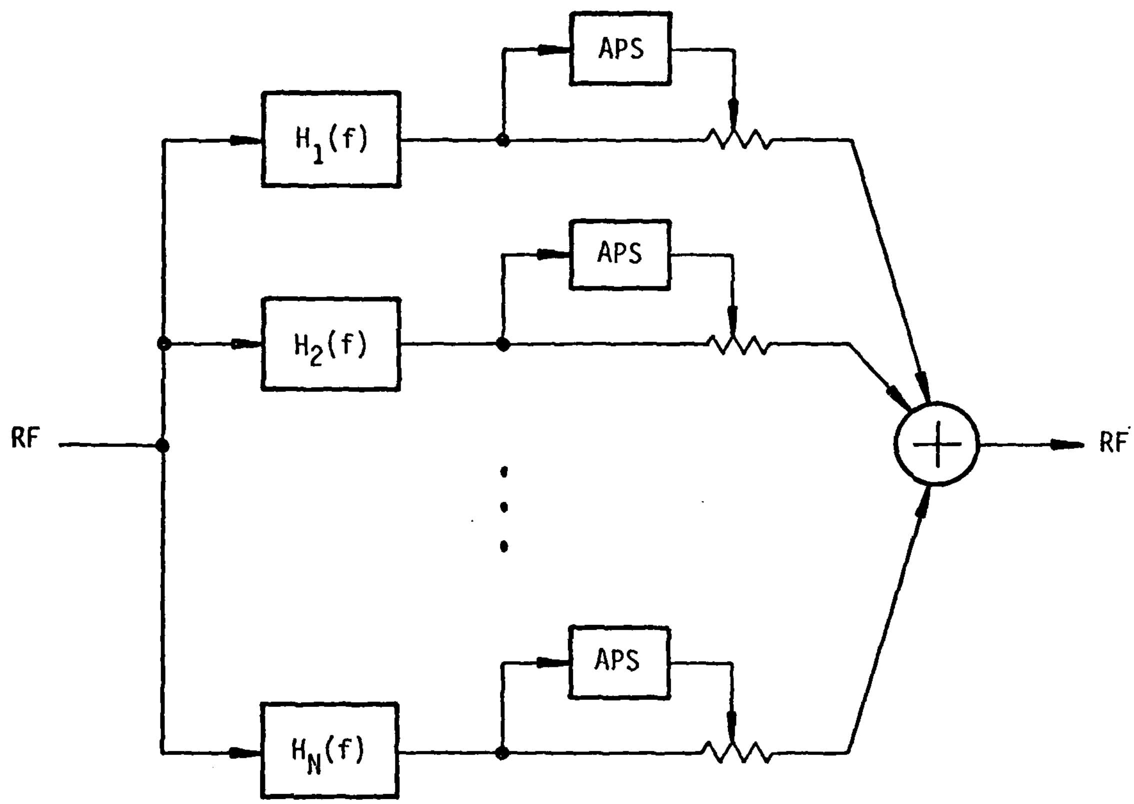
FIGURE 2-1

SINGLE-OUTPUT, SELF-ADAPTIVE OPTICAL EXCISOR



$H_i(f)$ = LINEAR PASSBAND FILTER RESPONSE OF THE ith CHANNEL

APS = AVERAGE POWER SENSE ELEMENT

 = VARIABLE GAIN ELEMENT

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FIGURE 2-2

MODEL OF THE SINGLE-OUTPUT, SELF-ADAPTIVE EXCISOR

The exact relationship between the average power in a frequency channel and the gain of that channel determines the adaption characteristics of the optical excisor. For narrowband frequency rejection, it is desirable reduce the channel gain as much as possible if the average power in that channel exceeds some threshold. For dynamic range compression, a more gradual decrease in channel gain versus average channel power is desirable.

Unlike other frequency selective limiters,[7,8] the narrowband frequency rejection process of the self-adaptive optical excisor does not generate spurious nonlinear intermodulation in the RF output. This is because the optical excisor adapts the gain of each frequency channel according to the average channel power rather than the instantaneous channel power. However, the adaption speed of the optical excisor can be shorter than the inherently long time delay between the RF input and RF output. As a consequence, it is potentially possible to construct an optical excisor whose RF output never contains narrowband interference above some set threshold.

In some applications, it is desirable to separately process both the narrowband and broadband signals. The dual-output, self-adaptive excisor meets this requirement by providing separate RF outputs for the high-level, narrowband signals and the low-level, broadband signals. This dual-output, self-adaptive excisor concept is shown in Figure 2-3. The dual output excisor, whether self-adaptive or programmable, has the inherent property that the sum of the RF outputs equals the RF input within a fixed time delay and scale factor. This useful property ensures that no signals are lost for post processing of the RF outputs.

For a variety of applications, it is desirable to program the filter response of the optical excisor under external control rather than in direct response to the power spectrum. This concept is shown in Figure 2-4. The external commands permit one to select which frequency channels are combined at the RF output. The external commands may originate from a manual operator or an electronic controller. The response time of the filter to electronic commands can potentially be extremely rapid.

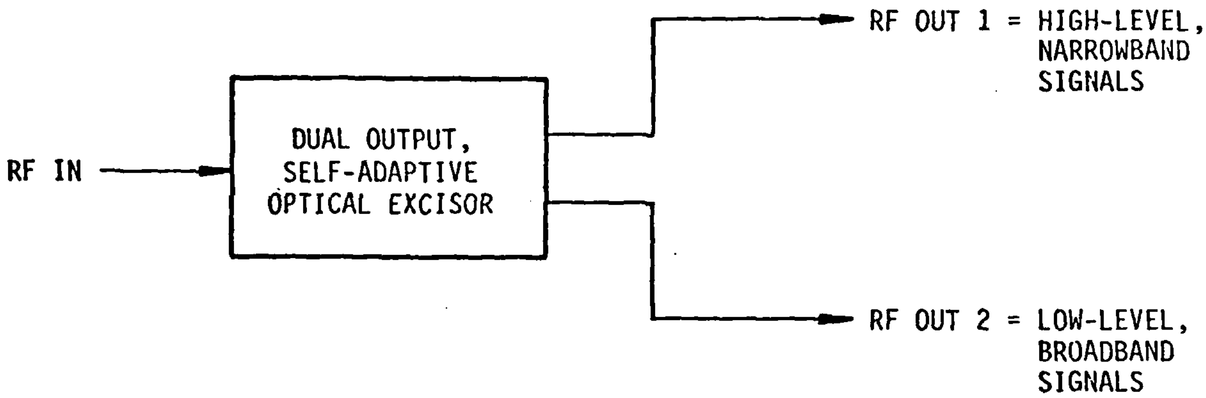

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FIGURE 2-3
DUAL-OUTPUT, SELF-ADAPTIVE OPTICAL EXCISOR

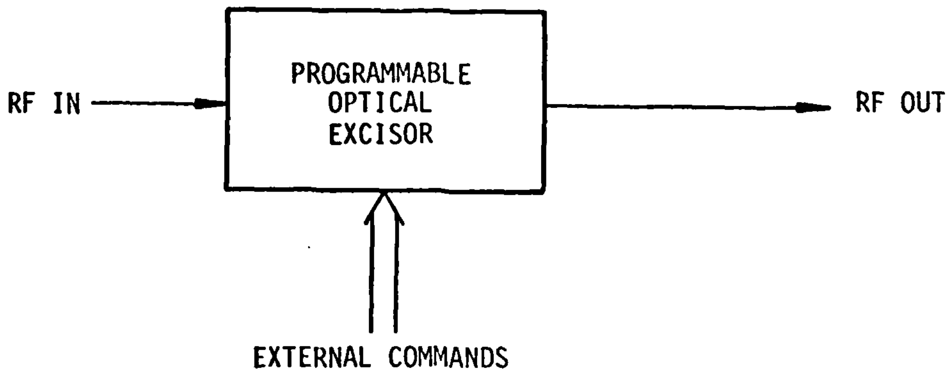

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FIGURE 2-4
SINGLE-OUTPUT, PROGRAMMABLE OPTICAL EXCISOR

The programmable optical excisor can also be configured with dual outputs as shown in Figure 2-5. In this case, each filter channel is switched to one of the two RF outputs according to the external commands. As a result, the sum of the RF outputs is equal to the RF input within a fixed delay and scale factor.

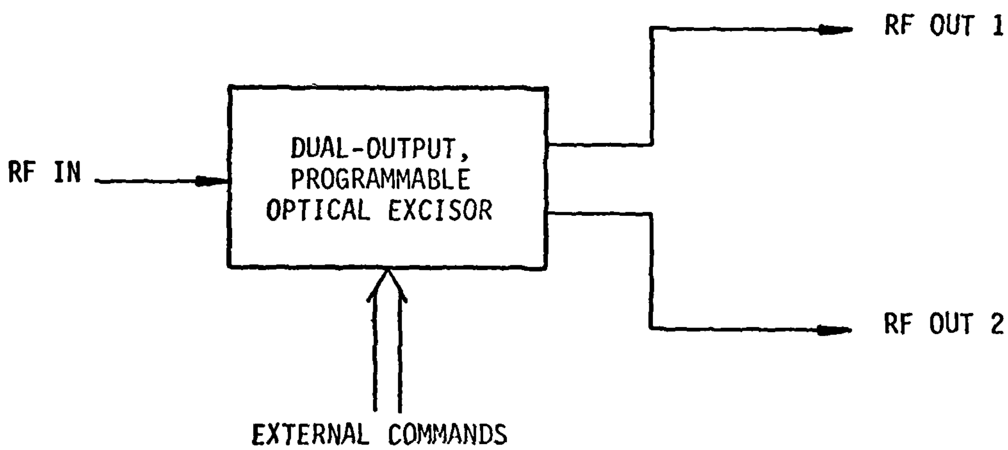

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FIGURE 2-5
DUAL-OUTPUT, PROGRAMMABLE OPTICAL EXCISOR

3.0 OPTICAL EXCISOR CONFIGURATIONS

The optical excisor types described in the previous section all have very similar configurations for their optical layout. Each configuration relies on coherent optical detection using an optical interferometer structure. There are two basic interferometer types which have been used for optical excision: the Mach-Zehnder interferometer and the holographic interferometer. The Mach-Zehnder interferometer for linear acousto-optic processors was first demonstrated over a decade ago(9) while the holographic interferometer for optical excisors was invented by PROBE SYSTEMS (patent applied for) and detailed measurements were made during the course of this contract.(1)

The optical layout for a single-output optical excisor using a Mach-Zehnder interferometer is shown in Figure 3-1. The optical beam from a spatially coherent laser source is collimated and split into separate signal and reference beams using a beam splitter. The optical signal beam is passed through a Bragg cell which modulates the optical beam with the RF input of the excisor. The modulated optical signal beam is spatially Fourier transformed by a lens so that the "instantaneous spectrum" of the RF input is represented by an optical intensity distribution in the lens transform plane.

Coherent detection of the modulated optical signal beam is achieved by combining it with the optical reference beam using a second beam splitter. The output photodetector spatially integrates the sum of the combined signal and reference beams. The cross term of this spatial integration results in the desired RF output.

The coherent detection process is entirely linear so that the RF output must be a linearly filtered version of the RF input. If the spatial light modulator of Figure 3-1 is removed, the RF output is equal to a delayed replica of the RF input providing the RF input is within the bandwidth limits of the Bragg cell and the photodetector. Inserting the spatial light modulator in the transform plan allows one to manipulate the magnitude of the signal Fourier components which are passed to the photodetector and the RF output. The number

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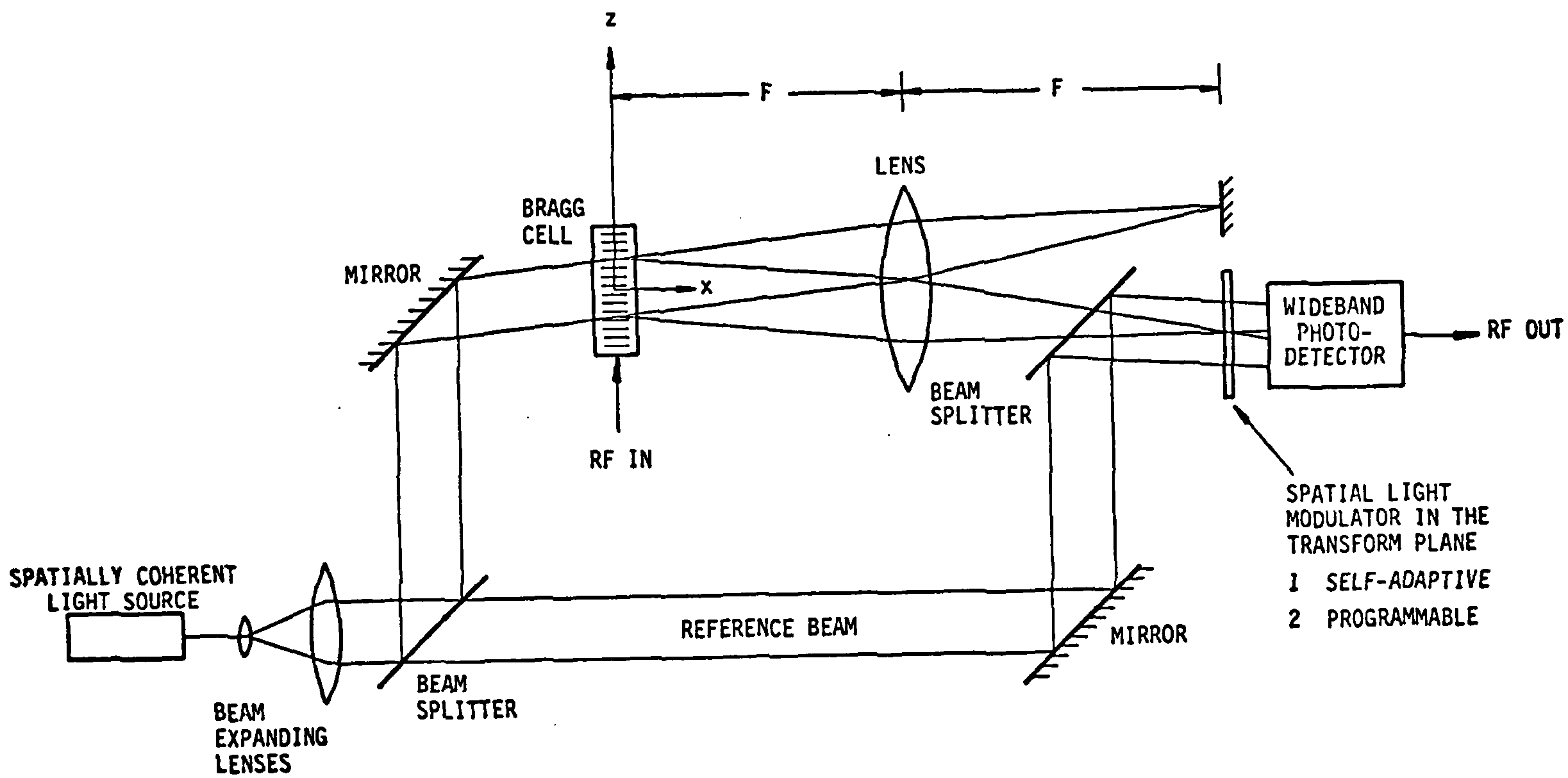

FIGURE 3-1

SINGLE-OUTPUT OPTICAL EXCISOR IMPLEMENTED WITH A MACH-ZEHNDER INTERFEROMETER of resolvable frequency positions or "channels" in the transform plane is somewhat less than the time-bandwidth product of the Bragg cell.

The spatial light modulator may be self-adaptive or programmable. A typical self-adaptive spatial light modulator acts as an "optical inverter" which attenuates intense optical signals above some threshold while passing the low-level optical signals unattenuated. Placing the optical inverter in the transform plane of the optical excisor causes the intense portions of the RF spectrum to be attenuated so they are blocked from reaching the RF output. Thus the optical inverter type of spatial light modulator results in a self-adaptive optical excisor useful for narrowband frequency rejection. A programmable spatial light modulator will result in a programmable optical excisor.

The spatial light modulator in the transform plane controls the magnitude of each frequency channel but has no effect on the phase of the RF signals. The phase of the RF output is determined by the relative optical phase of the reference beam and modulated signal beam. Optical phase aberrations introduced by the spatial light modulator introduce the same optical phase modulation for the signal and reference beams so that the relative phase of the signal and reference beams is not changed. As a result, the phase of the RF output of the optical excisor is unaffected by minor optical phase aberrations of the spatial light modulator.

For the Mach-Zehnder interferometer structure of Figure 3-1, the phase of the RF output is very sensitive to microphonic vibration. This is because microphonic vibrations move the mirrors and beam splitters of the interferometer and change the relative optical phase of the signal and reference beams. An optical path length change of only one-half optical wavelength ($\simeq 0.3 \mu m$) between the signal and reference beams will change the phase of the RF output by 180°.

It is important to note that microphonic phase modulation introduced by the Mach-Zehnder interferometer only affects the RF carrier phase and not the group delay of the optical excisor. More technically, the microphonic vibrations introduce a time varying phase shift $\phi(t)$ in the RF output where $\phi(t)$

is independent of the RF frequency. Also, the microphonic phase modulation has no effect on the RF signal amplitude. As a consequence, the Mach-Zehnder interferometer structure for the optical excisor can be used for processing of those RF signals whose important features are sensitive to group delay distortion but not RF carrier phase distortion.

For many modern communications, radar, and intercept receivers, the phase of the RF carrier must be very stable and not subject to microphonic noise variations. For these applications, a much more stable interferometer structure is needed than can be built with the Mach-Zehnder interferometer. The holographic interferometer developed by PROBE can provide the desired stability by completely eliminating microphonic phase noise from the interferometer.

Figure 3-2 shows a single output optical excisor implemented with a holographic interferometer. The optical signal beam path is the same as in Figure 3-1. However, the optical reference beam used for coherent detection is generated holographically. The hologram diffracts a small fraction of the undeflected beam to create an optical reference beam which falls on the output photodetector. Proper control of the amplitude and phase distribution of the holographic reference beam is required to obtain the desired RF frequency response for the excisor. The successful implementation of a holographic excisor has been described in a previous technical report.(1)

The holographic optical excisor does not suffer microphonic phase noise because the optical signal and reference beams travel along a common optical path. Vibrations do not introduce relative phase shifts between the optical signal and reference beams. As a result, the RF output of the optical excisor is very stable and ultra fine frequency analysis of the RF output can be performed.(4)

So far, the optical excisor has been shown to have a single RF output. A dual output optical excisor can be achieved if the transform plane spatial light modulator uses optical polarization rotation for modulation of the optical beam. A dual output optical excisor implemented with a holographic interferometer is shown in Figure 3-3.

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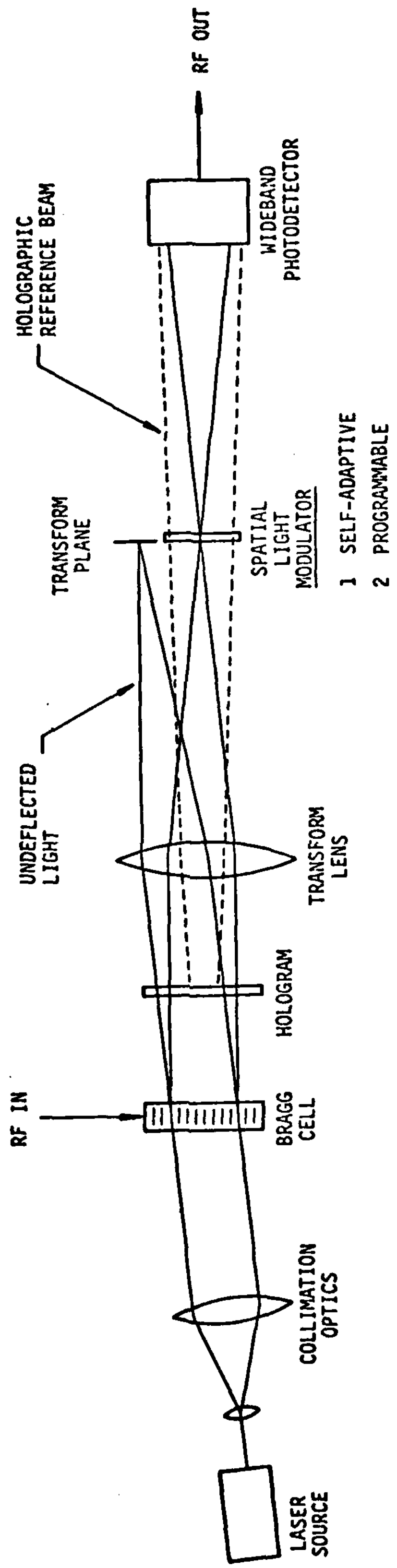

FIGURE 3-2

SINGLE-OUTPUT OPTICAL EXCISOR IMPLEMENTED WITH A HOLOGRAPHIC INTERFEROMETER

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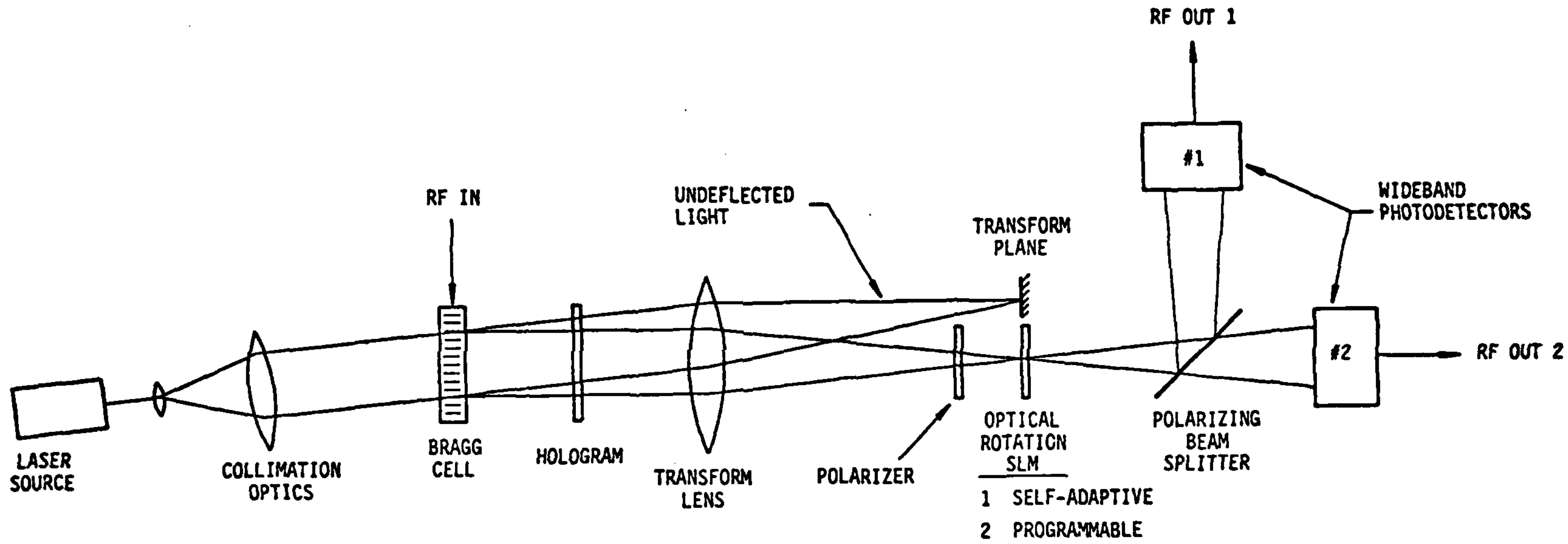

FIGURE 3-3

DUAL-OUTPUT EXCISOR IMPLEMENTED WITH A HOLOGRAPHIC INTERFEROMETER

The optical rotation spatial light modulator (SLM) acts to rotate the optical polarization of each frequency channel by 0° or 90° from the incident polarization direction. A polarizing beam splitter then separates the two orthogonal polarizations such that the 0° polarization is passed to one photodetector while the 90° polarization is passed to the other photodetector. Thus, the spatial light modulator uses optical polarization rotation to selectively pass the optical signal in each frequency channel to one of the two output photodetectors.

The optical rotation spatial light modulator only performs polarization rotation and any optical losses due to absorption or optical reflection are fixed. As a result, power conservation implies that the sum of the optical power in the 0° and 90° polarization directions must be proportional to the optical power incident of the spatial light modulator. This in turn dictates that the sum of the RF outputs of the dual output optical excisor must be proportional to the RF input (within a fixed time delay). This property is useful for post processors which must not discard any of the original input signal.

4.0 APPLICATIONS

The optical excisor types and configurations described in the previous section permit several fundamental types of filtering operations. These fundamental filtering operations have a large number of potential applications for modern wideband communications, radar, and intercept receivers as well as more general wideband signal processors. This section summarizes the fundamental filtering operations performed by optical excisors and then relates these operations to generic systems applications.

4.1 FUNDAMENTAL OPERATIONS

The following four fundamental, linear-filter operations are potentially feasible with optical excisor technology:

1. Adaptive rejection of narrowband interference,
2. Dynamic range compression without broadband intermodulation,
3. High Q bandpass and bandreject filtering,
4. Rapid programming of high Q bandpass and bandreject filters.

These basic filter operations are described briefly below.

Adaptive rejection of narrowband interference can be performed by a self-adaptive excisor which employs an optical inverter to reject portions of the signal spectrum above some threshold. Alternatively, a programmable optical excisor can be used for adaptive interference rejection by using spectral density information obtained from other processors to intelligently program the excisor. In either case, the optical excisor causes minimal degradation of the desired broadband signal because of the optical excisors ability to generate extremely narrow notch filter with essentially no phase distortion.

Dynamic range compression can be achieved in a variety of ways using optical excisors. As one example, one might consider a single-output, self-adaptive optical excisor which gradually attenuates portions of the signal spectrum as a function of signal power. As another example, one might consider a dual output excisor which adaptively separates the narrowband and broadband signals for use by separate post processors with limited dynamic range. Both the single and dual output optical excisor approaches for dynamic range reduction avoid the broadband intermodulation generated by most other techniques for dynamic range reduction and narrowband interference rejection.[5,7,8]

The optical excisor technology permits exceptionally high Q, programmable filtering over octave bandwidths. Independent control of each frequency channel permits complex filter functions to be generated such as multiple notch filters, comb filters, and multiple passband filters.

One can in theory program the frequency response of an optical excisor "instantaneously" despite its high filter Q. This is theoretically impossible with conventional filter types whose frequency response adaption time increases with filter Q. The optical excisor can achieve this instant filter response programming because it essentially consists of a bank of fixed, parallel filters whose outputs are selected under program control. If one selects or "programs" the optical excisor frequency response at a high rate while synchronously sampling the output, one can implement a large number of complex, high Q filters in parallel.

The optical excisor technology has the potential of gigahertz signal bandwidths with time-bandwidth products up to 1000. Extremely sharp filter skirts possible with no phase distortion near the filter skirts. Signal dynamic range on the order of 60 dB/MHz can be expected for small processors while 80 dB/MHz can be expected for larger processors incorporating higher power lasers. Further details on potential optical excisor performance levels can be found in Section 6.

It should be noted that no other technology is capable of the optical excisor functions at comparable bandwidths and dynamic range. Digital technology cannot currently achieve comparable bandwidths for reasonable size and power constraints. Also, the bandwidth of A/D converters is roughly a factor of ten lower than the bandwidth of todays acousto-optic devices. SAW chirp processors do not have the requisite broadband phase coherence and have difficulties in matching a large number of SAW devices for continuous I and Q channel processing. Additionally, SAW chirp excisors generate spurious broadband signals as a result of nonlinear clipping of narrowband signals.[8] Finally, SAW chirp processors cannot achieve the dynamic range and bandwidth of an optical excisor.

4.2 GENERIC SYSTEMS APPLICATIONS

The most obvious use for an optical excisor is as an IF or RF preprocessor for other wideband signal processors and receivers. The optical excisor can be programmed or adapted to reject undesired interference signals and noise while passing as much of the desired signal as possible. This in effect maximizes the signal-to-noise ratio while minimizing dynamic range requirements, thereby improving the performance of subsequent wideband signal processors.

While IF and RF preprocessors will probably dominate the near term applications of optical excisors, future systems can be envisioned which will utilize programmable optical excisors as building blocks much in the same way that microwave and SAW filters are used today. The rapid programming potential of an optical excisor gives it the ability to generate, track and downconvert frequency agile signals at rates well beyond other technologies. As such, programmable optical excisors may someday be used to generate and receive sophisticated spread spectrum signals which are extremely difficult to jam or intercept.

By providing narrowband interference rejection, dynamic range reduction, and frequency agile filtering, the optical excisor provides advanced capabilities for wideband signal processors and spread spectrum systems. Below is a list of generic applications which can utilize these capabilities of the optical excisor:

1. Spread Spectrum Communication and Radar Receivers
2. Spread Spectrum Intercept and Surveillance Receivers
3. Wideband Recording
4. Wideband Digitizing
5. Warning Receivers

6. Fast Frequency Synthesis
7. Fast Tracking Superhet Receivers

Items 1 through 4 above use the optical excisor as an IF or RF preprocessor while items 5 through 7 utilize the programmable optical excisor as a system building block. Each of the applications 1 through 7 is briefly discussed below.

4.2.1 Spread Spectrum Communications and Radar

Modern spread spectrum communication and radar receivers operate in a signal environment which is cluttered with overlapping narrowband and broadband signals.(10) Simultaneous processing of the overlapping narrowband and broadband signals poses a significant dynamic range and interference problem for the spread spectrum communication and radar receivers. The high-level, narrowband signals can quickly saturate the limited dynamic range of broadband SAW and digital correlators used for despreading the spread spectrum signal.(11) In addition, synchronization of the spread spectrum communications receiver is particularly difficult in the presence of narrowband interference and requires 10 to 14 dB higher signal-to-interference ratio than is required for communication once synchronization is achieved.(11) In some cases, the receiver synchronization can be even more difficult if the narrowband jammer frequencies are chosen to interfere with the receiver synchronization circuitry. As a result, narrowband signals from hostile and even friendly emitters pose a significant jamming threat to spread spectrum communications and radars.

The optical excisor can significantly reduce the narrowband jamming threat for spread spectrum communications and radar receivers. As shown in Figure 4-1, the optical excisor can precede the spread spectrum receiver to remove multiple narrowband jammers. The optical excisor can reject the narrowband signals by greater than 40 dB with extremely narrow notch filters having no phase distortion. These features provide narrowband interference

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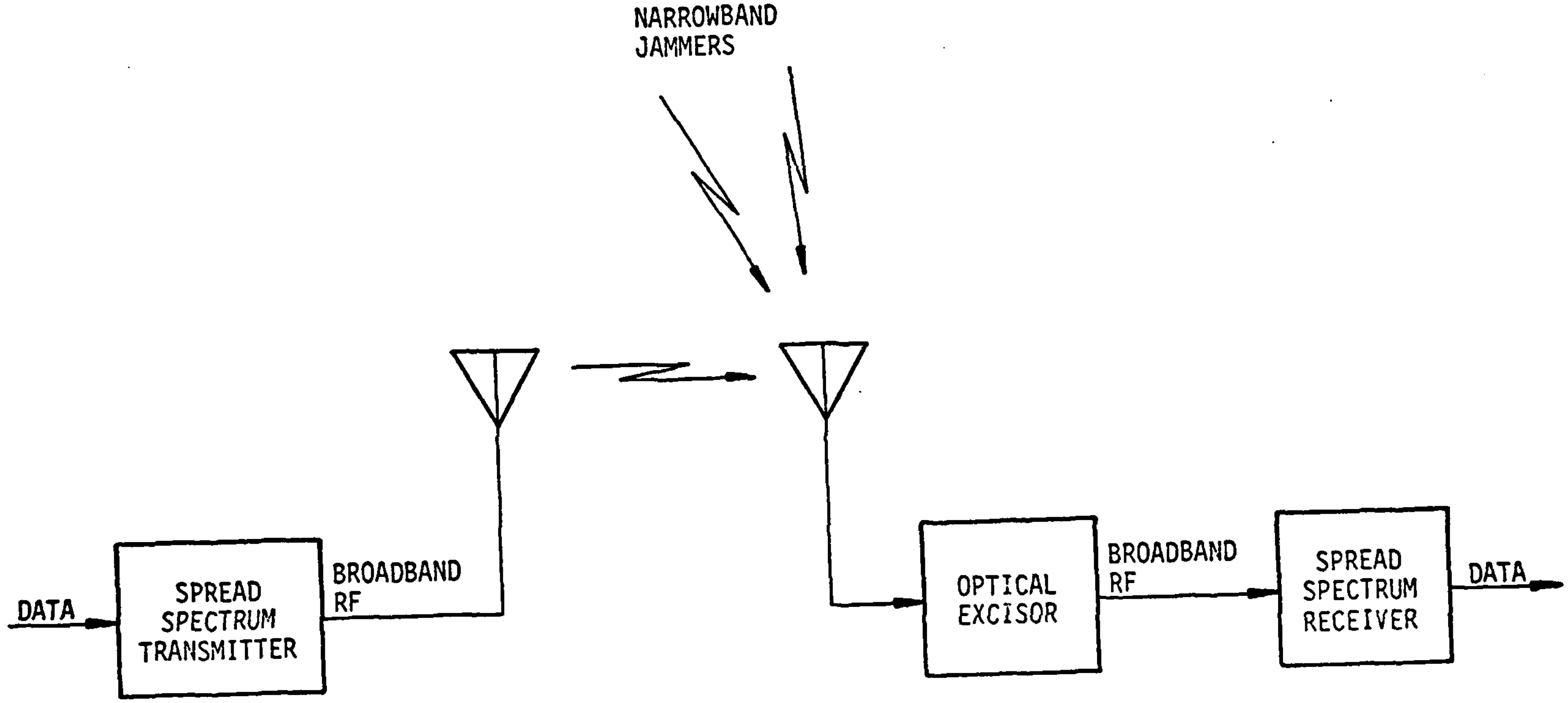

FIGURE 4-1

APPLICATION OF AN OPTICAL EXCISOR TO SPREAD SPECTRUM COMMUNICATIONS rejection with minimal degradation of the desired broadband spread spectrum signal.

4.2.2 Spread Spectrum Intercept and Surveillance Receivers

Intercept and surveillance receivers for spread spectrum signals face many of the same dynamic range and synchronization problems that the intended receiver faces. The sensitivity of radiometers used to detect the presence of spread spectrum signals is significantly degraded when the narrowband interference power exceeds the wideband noise power.[12] As shown in Figure 4-2, a dual output optical excisor can reduce the narrowband interference problem by separating the received RF signal into its narrowband and broadband components. The intercept receiver then separately detects and classifies the narrowband and broadband signals. The ability of the optical excisor to reject narrowband signals with extremely narrow filter notches having essentially no phase distortion ensures minimal degradation of the broadband signals for analysis by the intercept systems.

4.2.3 Wideband Recording

The dynamic range of analog signal recorders tends to decrease for wider recorder bandwidths. One can extend the limited dynamic range of wideband recorders by using the dynamic range compression and signal separation capabilities of the optical excisor. As shown in Figure 4-3, the dual output optical excisor filters the high-dynamic-range RF input into separate high-level narrowband signals and low-level broadband signals. The narrowband and broadband signals are separately recorded on wideband recorders. Since the sum of the two outputs of the dual output optical excisor must equal the RF input, the original RF input can be recreated with no loss of information from the two recordings.

This approach can provide a recording dynamic range improvement for RF signals whose narrowband signal power exceeds the wideband signal power. The amount of potential dynamic range improvement is in proportion to the ratio of the narrowband and wideband signal powers. Unlike other dynamic range

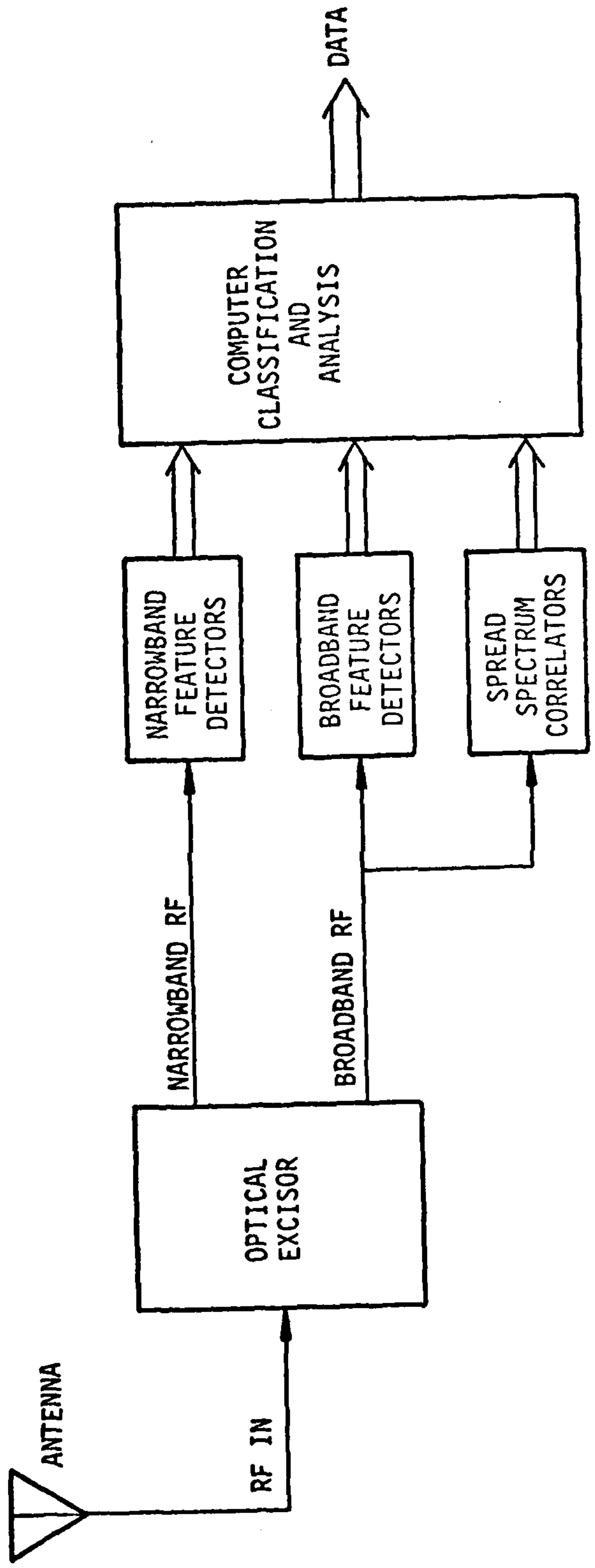

FIGURE 4-2
APPLICATION OF AN OPTICAL EXCISOR TO
WIDEBAND INTERCEPT AND SURVEILLANCE RECEIVERS

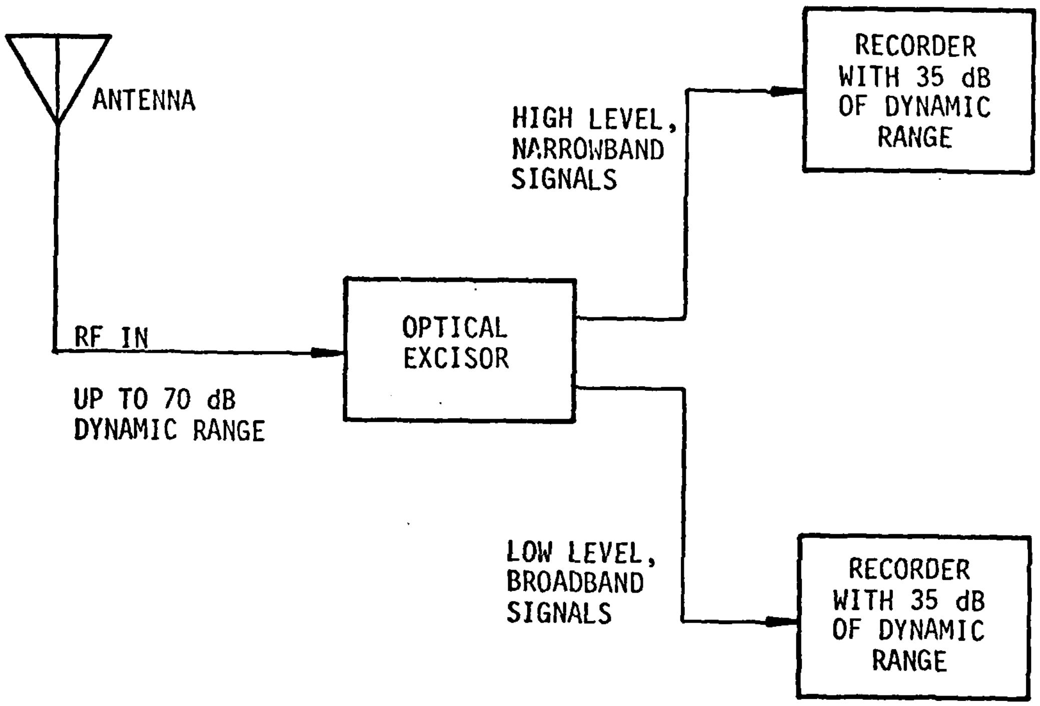

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FIGURE 4-3

APPLICATION OF AN OPTICAL EXCISOR TO
DYNAMIC RANGE IMPROVEMENT FOR
SIGNAL COLLECTION RECEIVERS

compression techniques, broadband intermodulation is avoided as a result of the frequency channelizing properties of the optical excisor.

4.2.4 Wideband Digitizing

Like the wideband recorder, the dynamic range of electronic A/D converters tends to decrease for wider bandwidths. As a consequence, digitization of broadband signals becomes impossible in the presence of high-level, narrowband interference signals which quickly saturate the dynamic range of the digitizer.

The optical excisor can separate the narrowband interference signals from the broadband signals and thereby reduce the dynamic range requirements of the digitizer. An additional benefit of the optical excisor is that the extremely steep filter skirts with no phase distortion provide excellent antialiasing for the digitizer. This permits the digitizer to operate with signal bandwidths close to the theoretical limit of one-half the sample rate. For variable sample rate digitizers, the optical excisor can function as a variable bandwidth antialiasing filter to match the sample rate.

4.2.5 Warning Receivers

The optical excisor technology can be used in a variety of warning receiver applications. One promising use for a programmable optical excisor is as a threat analyzer as shown in Figure 4-4. The optical excisor is programmed by an intelligent controller to pass signals in specific frequency bands. The RF power of the optical excisor output is sensed and fed back to the intelligent controller which stores the information in a threat bank.

The feedback loop of Figure 4-4 allows the controller to search for specific threats or detect changes in the signal environment. The optical excisor can potentially be programmed at very high speeds so that very rapid searching of many different types of threats can be performed in parallel. The

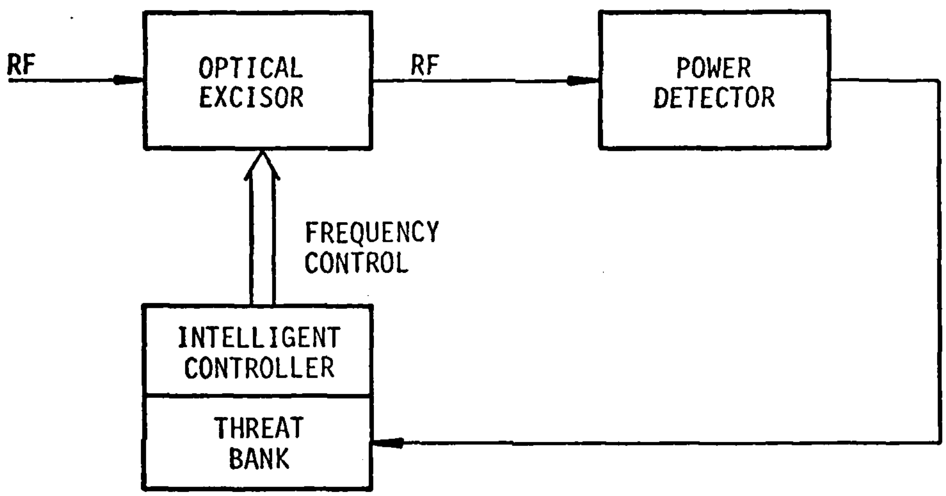

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FIGURE 4-4

OPTICAL EXCISOR USED AS A THREAT ANALYZER FOR DETECTING SPECIFIC THREATS OR CHANGES IN THE SIGNAL ENVIRONMENT intelligent controller can thus update and maintain an accurate threat emitter file.

4.2.6 Fast Frequency Synthesis

Synthesis of a high frequency CW carrier signal which has good frequency stability and rapid frequency hopping capability is highly desirable for modern spread spectrum communications and intercept systems. However, the speed at which one can synthesis the CW signal is inversely proportional to the settling time and phase noise of the CW signal for conventional phase-locked loop synthesis techniques.[13] Thus one cannot simultaneously achieve rapid frequency hopping and frequency stability with conventional frequency synthesis techniques.

In contrast to conventional techniques, the parallel filter properties of the optical excisor can be used to simultaneously achieve rapid frequency hopping and frequency stability. This technique is shown in Figure 4-5. The input to the optical excisor is an impulse train which is synchronized to a stable crystal oscillator. In the frequency domain, the RF input consists of a number of equally-spaced CW tones of equal amplitude and phase. The programmable optical excisor allows one to create a narrow passband filter to select one of these CW tones for the RF output while rejecting all of the other CW tones. The rate at which one can select one of the CW tones is theoretically unlimited but is in practice limited by the programming speed of the optical excisor. The programming speed of the optical excisor can potentially reach gigahertz rates with appropriate device development.

4.2.7 Fast Tracking Superhet Receivers

The frequency tracking rate of a superhet receiver is limited by the rate at which the input tuning filter and the local oscillator frequency can be adjusted. As a consequence, conventional superhet receivers have a tracking rate which is inversely proportional to the filter Q. Also conventional superhet receivers require an intermediate IF filter for image rejection before conversion to baseband can be achieved.

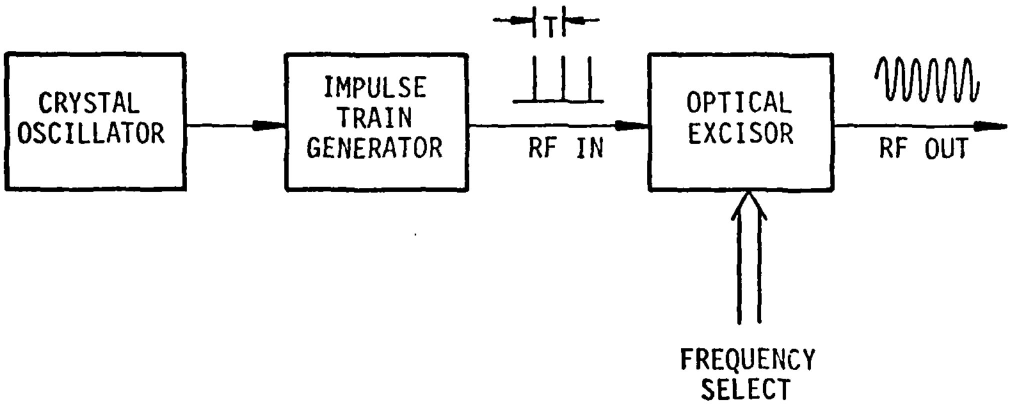

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FIGURE 4-5
FAST FREQUENCY SYNTHESIS USING AN OPTICAL EXCISOR

In contrast to conventional superhet receivers, a superhet receiver constructed with programmable optical excisors can simultaneously achieve fast tracking and high Q. Also, the requirement for an intermediate IF stage for image rejection can be avoided in many applications.

Figure 4-6 shows a superhet receiver constructed with optical excisor technology. The local oscillator frequency is selected using the fast frequency synthesis technique described previously in Section 4.2.6. An optical excisor is also used as a tuning filter for the RF input. The frequency skirts of the RF input are so sharp and deep that an intermediate IF filter is not required. Electronically mixing the filtered RF signal with the selected local oscillator frequency converts the signal directly to baseband.

The tracking rate of the superhet receiver is primarily limited by the rate at which the optical excisor can be programmed. The programming rate of the optical excisor can potentially be much greater than the bandwidth of the baseband signal which one is analyzing. As a result, it is possible to "time share" the superhet receiver to downconvert many different signals in parallel. This "time share" approach requires that the baseband output signal be sampled in synchronism with the frequency select instructions to the superhet receiver. The concept of time-sharing a high Q programmable filter for cownconverting several signals in parallel is currently under investigation[14] for downconversion of aircraft radio signals.

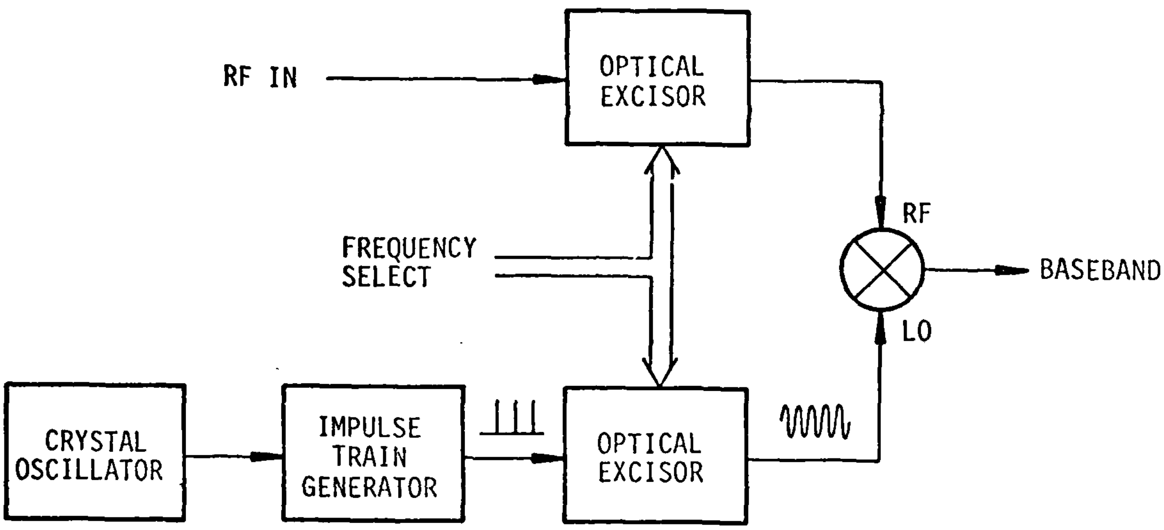

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FIGURE 4-6

FAST TRACKING SUPERHET RECEIVER USING AN OPTICAL EXCISOR

5.0 SUMMARY OF EXPERIMENTAL RESULTS

A large number of important experimental results were obtained during the optical excisor program. Breadboard and brassboard experiments resulted in four separate technical reports[1-4] in addition to this document. Field tests[4] demonstrated the utility of the optical excisor in a real world spread spectrum intercept system.

Most of the experimental results were obtained with off-the-shelf components having no major modifications. Exceptions to this rule were the holograms[1] which were fabricated by PROBE and a special photodichroic crystal[3] which was supplied by NRL. This allowed a maximum amount of conceptual verification and experimentation at a minimum of cost. The knowledge obtained from this experimentation is utilized in Section 6 to help specify future device requirements for optical excisors.

For a detailed summary of past results related to holographic detection, electronic and optical clippers, and field testing, the reader is referred to the previous technical reports.[1-4] For detailed data related to the optical excisor filter depth and signal dynamic range, the reader is referred to the new results presented in Appendix A of this report.

A very brief summary of the demonstrated performance levels of optical excisors tested by PROBE is presented in Figure 5-1. This data represents results from various experimental setups as opposed to results from a single optical excisor. For example, the adaptive filter experiments using the PROM spatial light modulator were performed with a 20 megahertz bandwidth Bragg cell which was apodized to resolve only 33 frequency channels. The phase distortion measurements were also performed with the 20 MHz bandwidth Bragg cells. The programmable filter data was taken using a 45 megahertz bandwidth Bragg cell which was apodized to resolve 200 frequency channels. The programmable filter data was taken using wires and razor blade apertures mounted on manually controlled translation stages for "manual" filter programming.

PERFORMANCE MEASURE	DEMONSTRATED VALUE
Bandwidth	45 MHz
Time-Bandwidth Product	450
Number of Frequency Channels	200
Center Frequency	70 MHz
Signal Dynamic Range*	64 dB @ 100 kHz noise bandwidth
Phase Distortion	±15° maximum
<u>Adaptive Filters</u> (PROM SLM)	
Notch Filter Depth	27 dB
Adaption Speed	1 second, maximum
<u>Programmable Filters</u> (Manual)	
Notch Filter Depth	40+ dB
Passband Filter Depth	50+ dB
Programming Speed	Several Seconds (manual)
Size	8 ft^3

*This signal dynamic range was measured for the time-bandwidth product of 450, a net filter bandwidth of 45 MHz, and a 7 milliwatt HeNe laser.

FIGURE 5-1
DEMONSTRATED PERFORMANCE LEVELS FOR OPTICAL EXCISORS

The signal dynamic range shown in Figure 5-1 was measured at a time-bandwidth product of 450, a net filter bandwidth of 45 MHz and a 7 milliwatt HeNe laser. Higher dynamic range can be achieved with a lower time-bandwidth product, a lower net filter bandwidth or a higher power laser.

While the demonstrated performance levels of Figure 5-1 are impressive, they should not be considered as performance limits of current technology. Rather, these performance levels to a large extent represent the limitations of the specific components used in the experiments. For example, the filter depth experiments implied that much deeper filter depths could be achieved using lower scatter optical components. Similarly, much wider bandwidths could be achieved using wider bandwidth Bragg cells and photodetectors which are currently available.

6.0 FUTURE REQUIREMENTS

The optical excisor technology has a large number of potential applications related to current and future electronic systems requirements. The experiments performed under the optical excision program showed that practical, high-performance optical excisors should be feasible with appropriate systems component development. This section summarizes future optical excisor performance goals and the component development required to achieve those goals.

6.1 OPTICAL EXCISOR PERFORMANCE GOALS

A reasonable set of performance goals for optical excisors which could be deployed during the next five (5) years is shown in Figure 6-1. These performance goals are believed to be in line with current technology modified to meet optical excisor requirements combined with on-going technology improvements for related acousto-optic processing systems. Of course, the exact rate at which the performance goals are achieved is closely related to the foresight of Government managers, the amounts of funding, and the expertise of the contractors.

One important aspect of the performance goals outlined in Figure 6-1 is the distinction between laser types. Multimode HeNe lasers are important for optical excisors with less than 200 megahertz of bandwidth but cannot be used for wider bandwidths due to the close frequency spacing of the longitudinal modes. Laser diodes and single mode high power lasers can avoid this problem. Also, there is a significant tradeoff in size and power versus dynamic range as a result of the laser choice.

6.2 DEVELOPMENT REQUIREMENTS

Much of the technology required to meet the optical excisor performance goals of Figure 6-1 can be adapted from on-going technology development in other related areas. For example, the requirements pull for acousto-optic spectrum analysis will result in the broadband Bragg cells, compact laser diodes and minibench modules required for optical excisors. Also,

PERFORMANCE MEASURE	GOAL			
	1983	1985	1987	
Bandwidth	150	500	2,000	MHz
Time-Bandwidth Product	500	1,000	1,000	
Number of Frequency Channels	250	300	500	
Center Frequency	280	750	3,000	MHz
Signal Dynamic Range				
HeNe Laser	70	X	X	dB @ 100-
Semiconductor Laser	70	75	80	kHz noise
High Power Laser	90	95	100	bandwidth
Phase Distortion	±10°	±3°	±2°	
Adaptive Filters				
Notch Depth	40	45	50	dB
Adaption Speed	100	1	0.5	μsec
Programmable Filters				
Notch Filter Depth	50	55	60	dB
Passband Filter Depth	60	65	70	dB
Programming Speed	1,000	1	10^{-3}	μsec
Size (including electronics)				
HeNe Laser	2	X	X	
Semiconductor Laser	0.5	0.1	0.02	ft^3
High Power Laser	8	6	4	
Power (including electronics)				
HeNe Laser	60	X	X	
Semiconductor Laser	50	30	20	Watts
High Power Laser	4,000	2,000	1,000	

FIGURE 6-1

PERFORMANCE GOALS FOR DEPLOYABLE OPTICAL EXCISORS high speed optical switches under development for fiberoptic communication are closely related to the optical switching needs of optical excisors. The single wideband photodetector required by the optical excisor can be a relatively straight-forward modification of wideband photodetectors currently used for fiber optics applications.

While much of the basic technology for optical excisors will be developed from other sources, adapting this technology specifically for use with optical excisors will require some effort. Also, specific technology and systems development directed uniquely at optical excisors will be necessary in order to meet the performance goals of Figure 6-1. The following sections briefly outline the technology needs and development requirements for optical excisors.

6.2.1 Adaptive Optical Inverter

A self-adaptive optical excisor requires an adaptive optical inverter element. A list of requirements for an adaptive optical inverter is shown in Figure 6-2. Each of these parameters is discussed briefly below.

The optical transmission of the inverter in the on state should be as high as possible to avoid losing optical power and therefore RF signal dynamic range. An optical transmission loss of less than 50% is considered reasonable since it will result in less than a 3 dB loss of RF signal dynamic range when the photodetection noise is dominated by optical shot noise. When the photodetector noise is dominated by thermal noise, a 50% optical transmission loss will result in a 6 dB loss of RF signal dynamic range.

The on/off intensity contrast ratio of the optical inverter should be greater than 100. This will permit notch filter depths of 40 dB at currently measured optical scattering levels. As optical scatter mechanisms are defined and eliminated in future work, inverter contrast ratios greater than 100 will be desirable.

PARAMETER	REQUIREMENTS
1. Optical Transmission in On State	Greater than 50%
2. On/Off Intensity Contrast Ratio	Greater than 100
3. Inverter Threshold Intensity	1 to 10^4 μw/cm^2 reasonable, exact value not critical
4. Number of Resolvable Spots	Up to 1000, 200 acceptable in many applications
5. Aperture Size	1 to 3 centimeters
6. Response Time	As low as 0.5 μsec, up to 1 millisecond permissible for many applications
7. Operating Wavelength	500 to 900 nanometers
8. Optical Flatness	Less than 5 waves/cm
9. Optical Scattering	Less than 1%
10. Inverting mechanism	
a. Dual Output Excisor	Optical polarization rotation
b. Single Output Excisor	Optical attenuation or polarization rotation
11. Support Equipment	"Low size and power"

FIGURE 6-2
OPTICAL INVERTER REQUIREMENTS

The exact value for the intensity threshold of the optical inverter is not critical since the optical intensity incident on the inverter may be scaled via the optics. A range of 1 to 10^4 $\mu W/cm^2$ is reasonable for the inverter threshold intensity.

An optical inverter with 1000 resolvable spots should be satisfactory for all current applications. An optical inverter aperture of 1 to 3 centimeters is desirable for compatibility with compact processor size. Many envisioned applications will only require 200 or so resolvable spots.

An optical inverter response time of roughly 0.5 microseconds will allow the optical excisor to separate narrowband and broadband signals before they ever appear at the optical excisor output(s). Many envisioned applications will tolerate excision response times of one millisecond or so.

The operating wavelength of the optical inverter should extend from 500 to 900 nanometers. This wavelength range corresponds to the wavelength range of the high efficiency silicon photodetectors, high efficiency acousto-optic modulators and high efficiency laser sources required for high performance optical excisors.

An optical flatness of 5 waves/cm is considered tolerable for the optical inverter since moderate phase aberrations of the optical inverter should not affect the optical excisor performance. Optical scattering should be less than 1% so that most of the optical beam passes through the optical inverter without random distortion.

It is preferred that the inverting mechanism of the optical inverter be based on optical polarization rotation. This will allow one to construct either a single or dual output excisor by following the optical inverter with a polarizing beam splitter. Optical inverters based on attenuation are only compatible with a single output excisor.

The support equipment for the optical inverter should be minimal to permit small size and power consumption for the optical excisor. Electrical power consumption of a few watts or less is desirable.

6.2.2 Programmable Optical Modulator

A programmable optical excisor requires a linear optical modulator array which can be externally programmed via an electronic interface. A list of requirements for the programmable optical modulator is summarized in Figure 6-3.

Many of the requirements for the programmable optical modulator are similar to those for the adaptive optical inverter. One important distinction for the programmable optical modulator concerns the interelement gap. If the optical beam passing through the gap is modulated normally off, then a relatively wide interelement gap can be tolerated. However, if the gap is normally on, then the gap width must be very small in order to maintain a high effective contrast ratio for interference rejection.

Another important aspect of the programmable modulator is its response time. Some applications such as interference rejection can tolerate a 0.5 microsecond response time since the inherent delay through the processor is typically greater than 0.5 microseconds. Other applications requiring ultrafast frequency agility for fast frequency synthesize, fast tracking superhet receivers and filter timesharing will require lower response times - conceivably as low as 1 nanosecond.

A variety of electronic interfaces to the programmable optical modulator can be envisioned for various applications. A serial interface will probably be suitable for many lower speed requirements while a quasi parallel interfaces will be required for higher speed applications. Integrating the electronic interface with the optical modulator material will require careful attention and can utilize a variety of hybrid bonding techniques or more sophisticated single-substrate technologies.

PARAMETER	REQUIREMENTS
1. Optical Transmission in On State	Greater than 50%
2. On/Off Intensity Contrast Ratio	Greater than 100
3. Number of Elements	Up to 1000 in linear array
4. Interelement Gap	
Gap Normally Off	Less than 10% of element width
Gap Normally On	Less than 1% of element width
5. Net Aperture	1 to 3 centimeters
6. Response Time	As low as 0.5 microseconds for interference rejection As low as 1 nanosecond for fast frequency agility
7. Electronic Interface	Highly application dependent
8. Operating Wavelength	500 to 900 nanometers
9. Optical Flatness	Less than 5 waves/cm
10. Optical Scattering	Less than 1%
11. Modulation Mechanism	
a. Dual Output Excisor	Optical Polarization Rotation
b. Single Output Excisor	Optical Polarization Rotation or Absorption
12. Support Equipment	"Low size and power"

FIGURE 6-3
PROGRAMMABLE OPTICAL MODULATOR REQUIREMENTS

6.2.3 Holograms

The holograms fabricated by PROBE for the optical excisor experiments were generated by exposing photographic plates with an interferometric optical system. The problems with this method include:

a. The laboratory procedure is very time consuming and expensive.

b. The results are difficult to reproduce.

c. The method is not suitable for diode laser wavelengths. (There is no practical good recording material for the near IR).

d. It is very difficult to correct system aberrations generated by the optics, the Bragg Cell, the laser beam profile and the photodetector response.

e. It is nearly impossible to synthesize a "general" frequency response for the linear acousto-optic filter.

f. High efficiency holograms are not feasible without distortion and scattering.

g. Optical scattering from the hologram limits the optical excisor filter depth.

As a consequence of the above hologram fabrication problems, investigation of more efficient hologram synthesis methods will be required before high-performance, highly-stable optical excisors can be economically produced.

6.2.4 Photodetectors

The bandwidth capabilities, wavelength response and dynamic range of silicon PIN and avalanche photodiodes are ideally suited to optical excisor requirements. However, off-the-shelf photodiodes do not have the specific geometry required for optical excisors. Also, off-the-shelf photodiodes are frequently not optimized for linearity at the optical intensity levels found in optical excisors. As a consequence, the potential signal dynamic range, bandwidth and filter resolution of the optical excisor cannot be achieved with current photodiodes. To obtain the full optical excisor performance, specific-geometry, wideband, silicon photodiodes optimized for optical excisor applications should be developed.

6.2.5 Laser Sources

A number of laser sources in the 500 to 900 nanometer wavelength range can be considered for use with optical excisors. Particular wavelengths of interest include 750 to 900 nanometers for compact GaAs laser diodes, 633 nanometers for low cost HeNe lasers, and 514 nanometers for high power argon lasers. Relatively new developments with alexandrite lasers hold promise for high power lasers in the 700 to 800 nanometer range.

Perhaps the most important lasers for future compact optical excisors are GaAs based laser diodes. The optical excisor requirements for these laser diodes are very similar to the requirements in acousto-optic spectrum analysis. Maintaining spatial coherence and narrow line widths are important to achieve the potential filter resolution of the optical excisor. High optical power output from the laser diode is particularly important for optical excisors in order to achieve high signal dynamic range.

6.2.6 Bragg Cells

The optical excisor requirements for Bragg cells are similar to the requirements for acousto-optic spectrum analyzers. However, special care must be taken in the design of the acousto-optic modulator to avoid severe phase distortion. This is because the optical excisor is a coherent processor while the spectrum analyzer is an incoherent processor. Also, optical excisor applications prefer (but do not require) that the diffracted beam generated by the Bragg cell have the same polarization as the undiffracted beam for maximum efficiency in the coherent detection process.

6.2.7 Component Integration

Future integration of components into practical optical excisors will require a significant amount of component integration. Stable but flexible modules should be developed to accept the various optical excisor components, lenses, and electrical connections. These modules can potentially be identical to the modules required for acousto-optic spectrum analysis if the adaptive optical inverters and programmable optical modulators are compatible.

6.2.8 Advanced Development Models

In order for optical excisors to be field tested for specific applications, advanced development models (ADM's) must be fabricated. These ADM's should be targeted for specific requirements as much as possible. Some applications require high dynamic range and can tolerate moderate size and power constraints. Other applications are driven by low size and power constraints yet can tolerate moderate dynamic range. Thus it is logical to develop two different types of advanced development models. One ADM would use compact GaAs laser diodes for small processor size and power. The other ADM would use high power lasers for the ultimate in dynamic range.

6.3 FIELD TESTING

In order to verify the performance and benefits of optical excisors, field testing must be a part of future work. This field testing can be used to provide the essential link between systems requirements and technology development.

APPENDIX A

A. Optical Excisor Dynamic Range

There are two basic classes of dynamic range measurements which one can associate with an optical excisor. One class of dynamic range measurements relate to the depth of the filter response for rejecting undesired frequencies. The other class of dynamic range measurements relate to the relative power of the signal noise and intermodulation products at the output of the optical excisor. The experimental results for these two classes of dynamic range measurements are described below and compared with theory.

A.1 Filter Response Depth

The filter response depth of an optical excisor is determined by a variety of factors. Even if one has an ideal laser with distortionless optics, the filter depth is limited by the inherent sidelobes of the optical spot in the Fourier transform plane. Optical distortions and scattering from the optics can further reduce the filter depth. Spatial wavefront distortions in the laser beam profile are another source of reduced filter depth as well as reduced frequency resolution. Broad laser linewidths and spontaneous emission can also reduce the filter depth and frequency resolution of the optical excisor.

For good overall filter depth, it is desirable to apodize the Bragg cell aperture such that its spatial Fourier transform produces a small, low-sidelobe optical spot in the transform plane. The absence of sidelobes prevents spillover of signal energy into adjacent frequency channels. This signal energy spillover will in general reduce the filter depth.

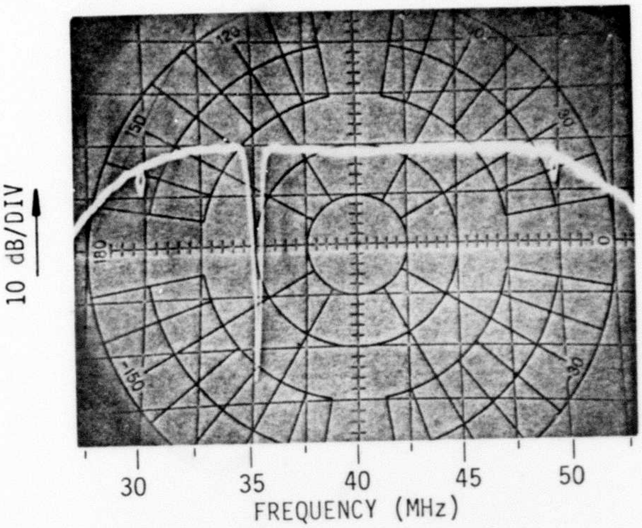
For most applications, appropriate apodization of the Bragg cell aperture can be achieved by illuminating the Bragg cell aperture with the natural laser beam profile. This typically results in a near gaussian, apodization truncated to the width of the Bragg cell aperture. Decreasing the amount of truncation tends to decrease the sidelobes of the Fourier transform plane spot which results in improved filter depth. However, decreasing the amount of truncation lowers the frequency resolution of the filter. Thus there is a tradeoff between filter depth and filter resolution.

Computer simulations[5,6] have been used to study this tradeoff between filter resolution and filter depth. These simulations assume an ideal laser and distortionless optics. With rectangular apodization, the number of resolvable frequency channels is approximately equal to the time-bandwidth (TB) product of the Bragg cell while the filter depth to the first sidelobe peak is a meager 22 dB. For truncated gaussian apodization, one can theoretically achieve much greater filter depths with only a moderate loss in frequency resolution. As an approximate example, truncated gaussian apodization can provide a filter depth to the first sidelobe of 45 dB while suffering a loss in frequency transition width of only a factor of 2 when compared to rectangular apodization.

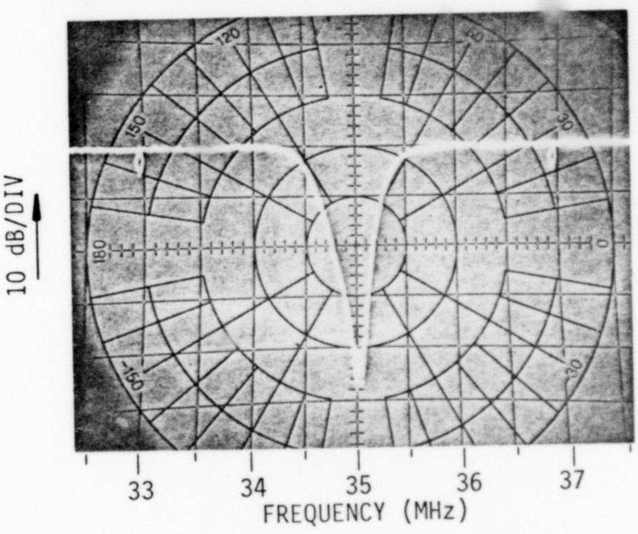
Experimental results were collected to determine the optical excisor filter depth for typical narrowband notch filters and passband filters. These experiments utilized a seven milliwatt Spectraphysics laser, model 120. Notch filters were created by placing an opaque wire in the Fourier transform plane while passband filters were created by placing a razor blade aperture in the transform plane.

The filter depth experiments were performed with two different Bragg cells. One Bragg cell was an Anderson Laboratories BD-125 which has a time-bandwidth product of 125 and a frequency range of 28 to 52 megahertz. The other Bragg cell was an IntraAction AOD-70 which has a time-bandwidth product of 400 and a measured frequency range of 50 to 95 megahertz. Both of these Bragg cells use glass as the acousto-optic medium. Each Bragg cell used a slightly truncated laser beam profile to produce a nearly gaussian apodization for good filter depth.

A typical example of a narrowband notch filter created with the optical excisor is shown in Figure A-1. This data used the low bandwidth Bragg cell and was collected using a network analyzer to display the magnitude response versus frequency of the optical excisor. The narrow notch was created using a wire in the transform plane whose width was equal to 1/33 of the net bandwidth of the optical excisor.



A. MAGNITUDE RESPONSE



B. MAGNITUDE RESPONSE, EXPANDED VIEW

FIGURE A-1

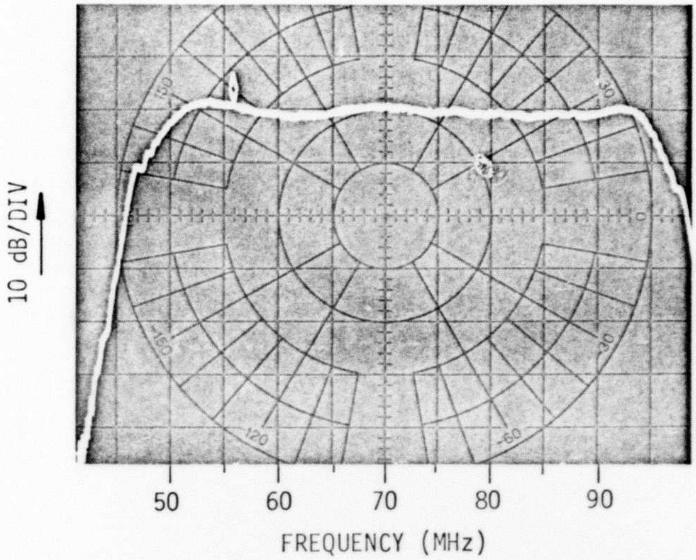
NOTCH FILTER DEPTH FOR AN OPTICAL EXCISOR
USING NEARLY GAUSSIAN APODIZATION

One can see that the narrowband notch filter is very deep, in excess of 40 dB. The excision depth near the notch center is very jagged and varies from 40 to 48 dB in depth. This jaggedness is believed to be caused primarily by optical scatter. Other experiments using wider wires in the transform plane created wider filter notches, but the notch depth was limited in the range at 40 to 50 dB. Thus 40 dB appears to be a practical notch filter depth which one can guarantee with the experimental setup used. It is believed that much higher notch filter depths can be achieved if lower scatter optics are used. Notch filter experiments using the wider bandwidth Bragg cell demonstrated very similar performance in the notch filter depth.

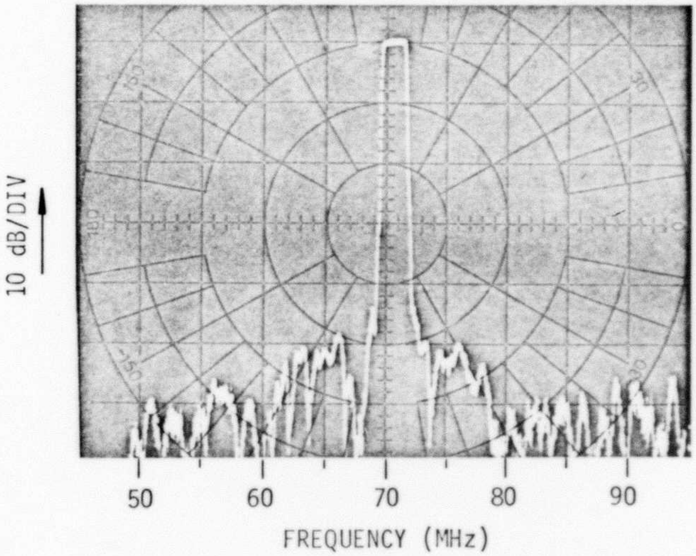
A typical example of the filter depth for a narrow passband filter implemented with the optical excisor is shown in Figure A-2. This data was collected using the broadband Bragg cell. Figure A-2A shows the frequency response for the optical excisor operating at full bandwidth. One can see that the frequency response is relatively flat over 45 megahertz of bandwidth. Figure A-2B shows the frequency response for the optical excisor operating as a narrow passband filter. This passband filter was created using a razor blade aperture in the transform plane.

One can see from Figure A-2B that the passband filter response allows approximately 50 dB of rejection near the filter skirts and approximately 60 dB of rejection farther from the skirts. This represents 10 to 20 dB more filter rejection than was obtainable with the notch filters. This superior filter performance for the passband response strongly suggests that optical scattering is limiting the filter depth. The passband filter blocks most of the light in the Fourier transform plane while the notch filter passes most of the light in the Fourier transform plane. As a consequence, the passband filter blocks more optical scattering than the notch filter and thereby achieves better filter depth.

The experimental filter depth results shown here are quite impressive and compare favorably with the capabilities of fixed SAW filters. The filter rejection for a typical fixed passband filter implemented with commercial SAW technology is on the order of 45 dB[15] while the optical excisor



A. MAGNITUDE RESPONSE, FULL BANDWIDTH



B. MAGNITUDE RESPONSE, NARROW PASSBAND

FIGURE A-2

FULL BANDWIDTH AND NARROW PASSBAND
FREQUENCY RESPONSES FOR AN OPTICAL EXCISOR

passband filter results shown here demonstrate 50 dB of filter rejection depth. Perhaps most importantly, the experimental results suggest that filter depths much greater than 50 dB may be possible through the use of low scatter optics and careful optical design.

A.2 Signal, Noise and Intermodulation Power

When viewed as a module, the optical excisor is an active device which consumes electrical power and has an electronic RF input and output. It is very similar to a two port electronic amplifier combined with a high Q filter network. Like the electronic amplifier, the optical excisor has sources of internal noise as well as limits on the RF signal level, so its signal dynamic range is limited.

The signal dynamic range of the optical excisor can be described in terms very similar to those used for describing the dynamic range of electronic amplifiers. This involves specifying the relative power levels of signal, noise and intermodulation. One useful dynamic range measure is the maximum signal-to-noise (S/N) ratio which can be achieved at the optical excisor output. For purposes of standardization, this maximum signal-to-noise ratio is often measured at the 1 dB compression point of the fundamental output signal for a single frequency input signal.

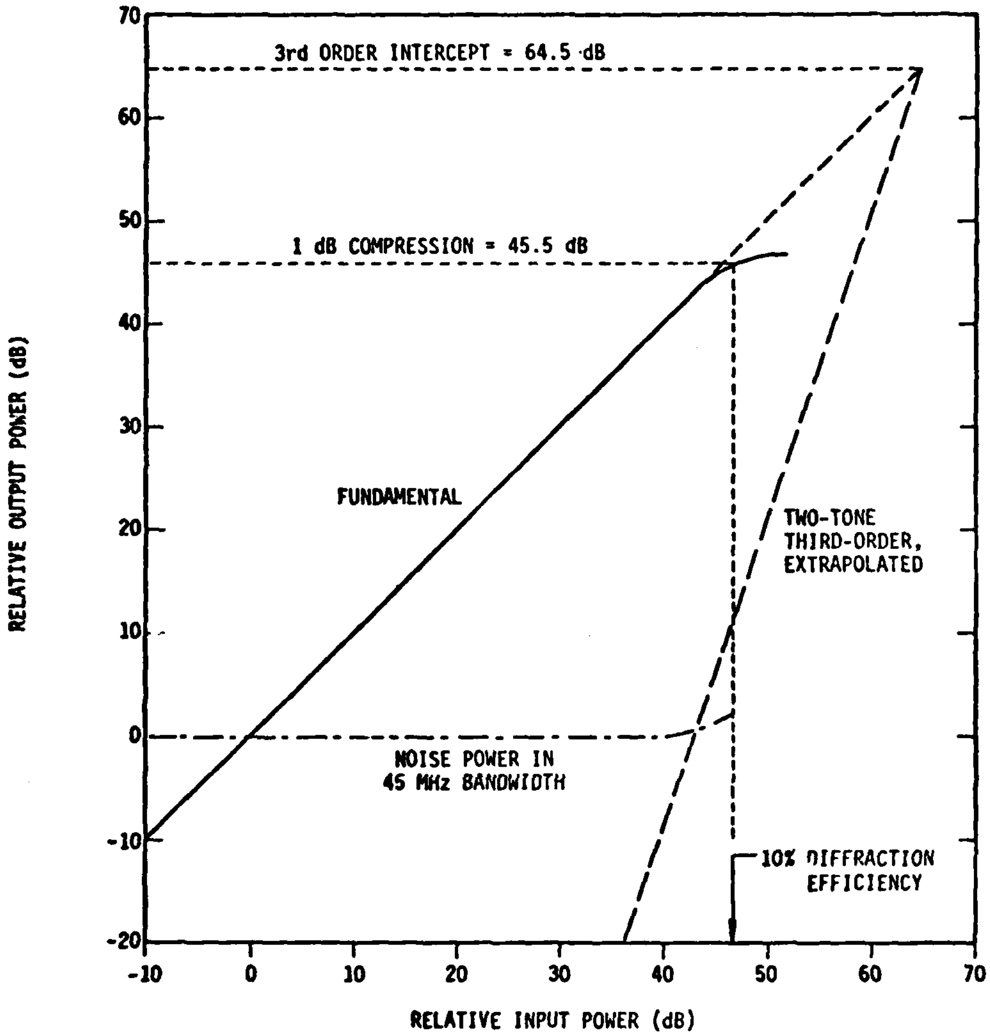
Another useful measure of dynamic range is the third-order intercept point[16] relative to the noise floor. The third order intercept point represents the hypothetical signal level for which the extrapolated fundamental response intersects the extrapolated, two-tone, third-order intermodulation product response. If the intercept point of the optical excisor relative to the broadband noise power level is given by I dB, then the spectral free dynamic range of the optical excisor is given by 2/3 I dB.[16] In general terms, the spectral free dynamic range represents the maximum output signal-to-noise ratio for which the two-tone, third-order intermodulation products do not exceed the broadband noise power.

The noise power at the optical excisor output contains contributions from optical poisson shot noise caused by photoelectron generation, photodetector excess noise caused by random photodetector gain, photodetector circuit noise, and optical excess noise from the laser source. In addition, the noise level can be dependent on the filter function selected as well as the signal power level. The maximum relative signal power may be limited by a variety of factors such as a maximum input optical power of the photodetector, a maximum diffraction efficiency of the Bragg cell, or signal compression caused by the acousto-optic diffraction process. The output signal-to-noise ratio is also affected by such things as the time-bandwidth product of the filtering operation, the optical source power, the fraction of the optical power in the signal versus the reference beam. the fractional usage of the optical signal and reference beams, and the relative amplitude variations of the signal and reference beams in a direction perpendicular to the acoustic beam propagation.

In reference 6, the broadband output signal-to-noise ratio of the optical excisor is optimized. This optimization assumes that the maximum signal level is limited by a maximum acousto-optic diffraction efficiency of the Bragg cell. One can use these optimized results to compare the theoretical dynamic range of an optical excisor versus the experimental dynamic range results.

In Figure A-3, the theoretical signal, wideband noise and intermodulation power levels for an optimized optical excisor are shown. This theoretical data assumes a net optical excisor bandwidth of 45 megahertz, a Bragg cell time-bandwidth product of 400, a 7 milliwatt HeNe laser, and a PIN photodiode detector with a quantum efficiency of 50%. The saturated signal level is assumed to be determined by the Bragg cell input power limit such that the 1 dB compression point occurs at a diffraction efficiency of 10%. Other assumptions pertinent to the optimization can be found in reference 6.

From Figure A-3, one can see that the theoretical 1 dB compression point of the optical excisor occurs at a relative output power of 45.5 dB. The noise power increases for signals near the 1 dB compression power level due to signal dependent optical shot noise. As a result, the noise power level at the 1 dB compression point is at a relative power of +2 dB. Thus the theoretical



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ASSUMPTIONS

1. 7 MILLIWATT HeNe LASER
2. TIME-BANDWIDTH PRODUCT OF 400
3. PIN PHOTODIODE DETECTOR WITH 50% QUANTUM EFFICIENCY
4. SATURATED SIGNAL LEVEL DETERMINED BY BRAGG CELL LIMITS

FIGURE A-3

THEORETICAL DYNAMIC RANGE OF AN OPTIMIZED OPTICAL EXCISOR HAVING A NET BANDWIDTH OF 45 MEGAHERTZ output signal-to-noise ratio at the 1 dB compression point of the optical excisor is 45.5 - 2 = 43.5 dB.

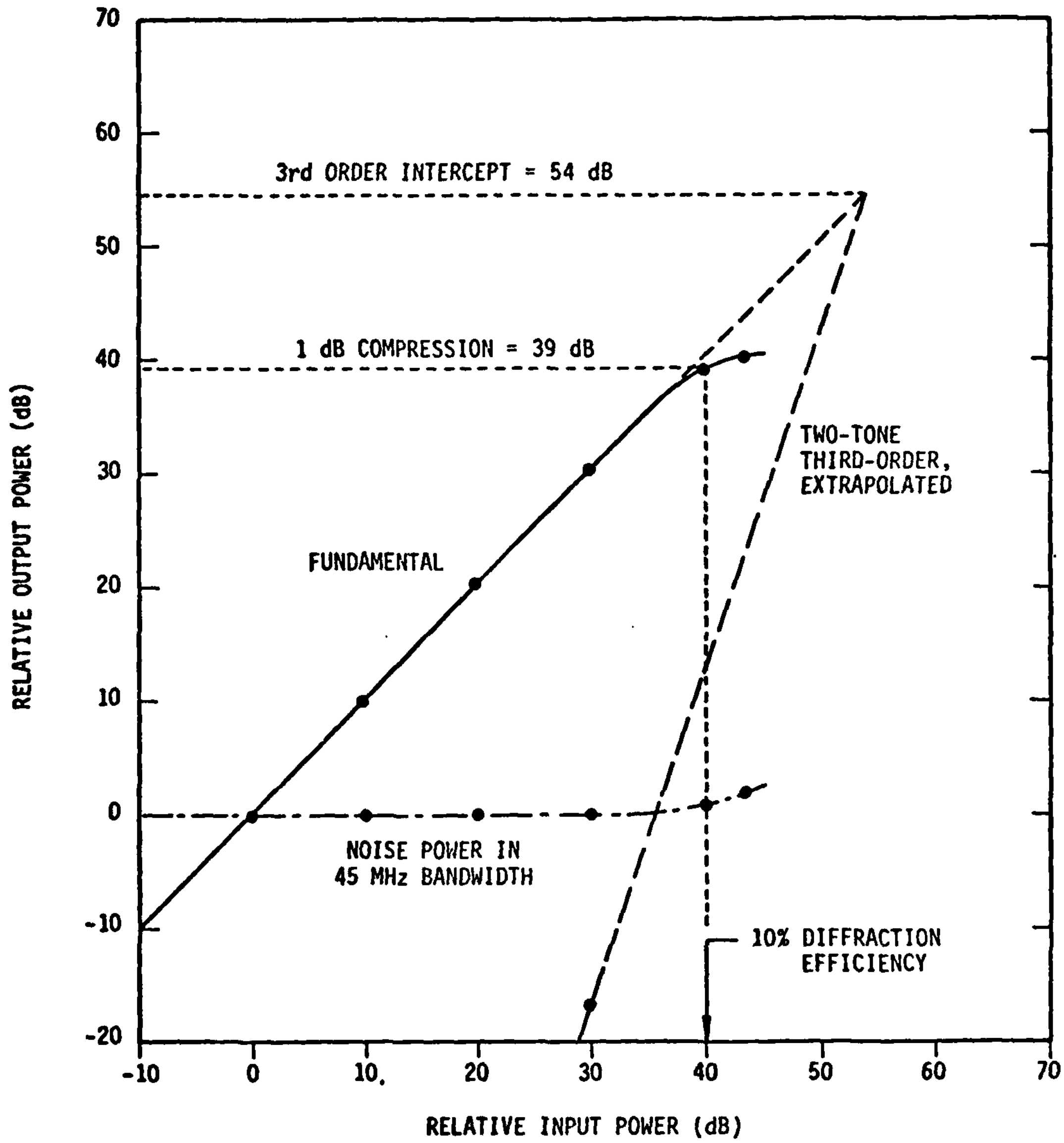
The theoretical two-tone, third-order intermodulation power for the optical excisor are also plotted in Figure A-3. This intermodulation is assumed to be caused by the acousto-optic diffraction process of the Bragg cell. The third order intercept point occurs at a power level of 64.5 dB relative to the noise floor so that the theoretical spectral free dynamic range of the optical excisor is 43 dB.

Experimental measurements for the signal, wideband noise and intermodulation power were taken using an optical excisor configured for 45 megahertz of bandwidth. The frequency response of this optical excisor was shown previously in Figure A-2. Figure A-4 shows the experimental results of these dynamic range measurements.

The conditions for the experimental data in Figure A-4 are essentially the same as the assumptions for the theoretical data of Figure A-3 except that an avalanche photodiode detector is used rather than a PIN photodiode detector. As one consequence, the saturated signal level for the experimental results is determined by the input optical power limits of the avalanche photodiode rather than the power limits of the Bragg cell. Another consequences of using an avalanche photodiode rather than a PIN photodiode is excess shot noise.

The experimental results of Figure A-4 show a signal-to-noise ratio at the 1 dB compression point of 39 - 1 = 38 dB. This is 5.5 dB lower than the theoretical value of 43.5 for the optimized optical excisor. The lower signal-to-noise ratio for the experimental results can be attributed to factors such as excess shot noise from the photodetector and optical reflection losses.

The third-order intercept for the experimental results of Figure A-4 is at 54 dB relative to the wideband noise floor. Thus the spectral free dynamic range for the experimental optical excisor is 36 dB which is 7 dB lower than the theoretical value. One can see that the two-tone, third-order



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CONDITIONS

1. 7 MILLIWATT HeNe LASER
2. TIME-BANDWIDTH PRODUCT OF 400
3. AVALANCHE PHOTODIODE DETECTOR
4. SATURATED SIGNAL LEVEL DETERMINED BY PHOTODETECTOR

FIGURE A-4

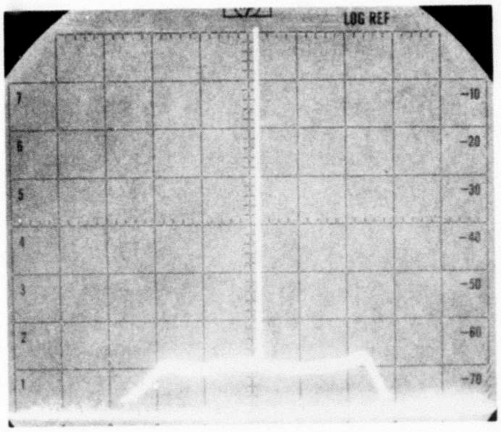
MEASURED DYNAMIC RANGE OF A TYPICAL OPTICAL EXCISOR HAVING A NET BANDWIDTH OF 45 MEGAHERTZ intermodulation for the experimental optical excisor is much higher than one would predict from the acousto-optic diffraction process of the Bragg cell. The excess third-order intermodulation level is believed to be caused by the input and output amplifier electronics of the optical excisor and should be removable by proper system design.

As verification of the experimental dynamic range measurements, Figure A-5 contains photographs of the output signal noise and intermodulation power levels for an optical excisor as measured with a spectrum analyzer. The spectrum analyzer noise bandwidth was 30 kHz for this data. Figure A-5A shows the optical excisor output at the 1 dB compression point for a single frequency input. The signal-to-noise level is seen to be 70 dB for the 30 kHz noise bandwidth which translates to 38 dB for the 45 MHz bandwidth of the optical excisor. This agrees exactly with Figure A-4. Figure A-5B shows the two-tone response of the optical excisor and the indicated intermodulation product levels also agree with Figure A-4.

The experimental dynamic range results shown above agree with the theoretical dynamic range model within a few dB. Also, the experimental results are expected to match the theoretical results more closely when the individual optical excisor components are optimized. It is therefore reasonable to use the theoretical dynamic range model for predicting the dynamic range of other optical excisor component configurations.

Figure A-6 shows the theoretical maximum wideband signal-to-noise ratio at the output of an optical excisor versus net filter bandwidth. The output signal-to-noise ratio under shot noise limited conditions is proportional to the laser power and laser wavelength. As a result, the higher power argon laser of Figure A-6 shows a 20 dB higher output signal-to-noise ratio than the laser diode and should in theory permit very high dynamic range optical excisors. However, the argon laser will consume much more power and space than the laser diode, so there exists a tradeoff between dynamic range and processor power/size.

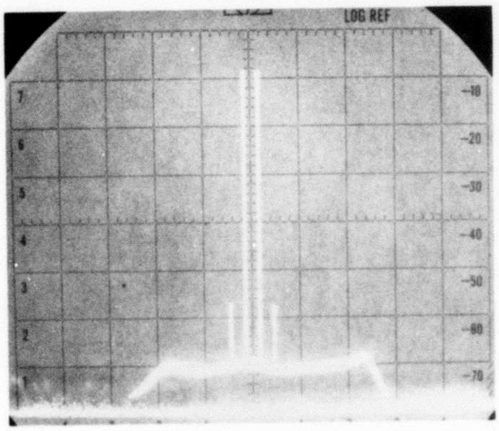
10 dB/div



10 MHz/div

A. FUNDAMENTAL RESPONSE AT 1 dB COMPRESSION

10 dB/div

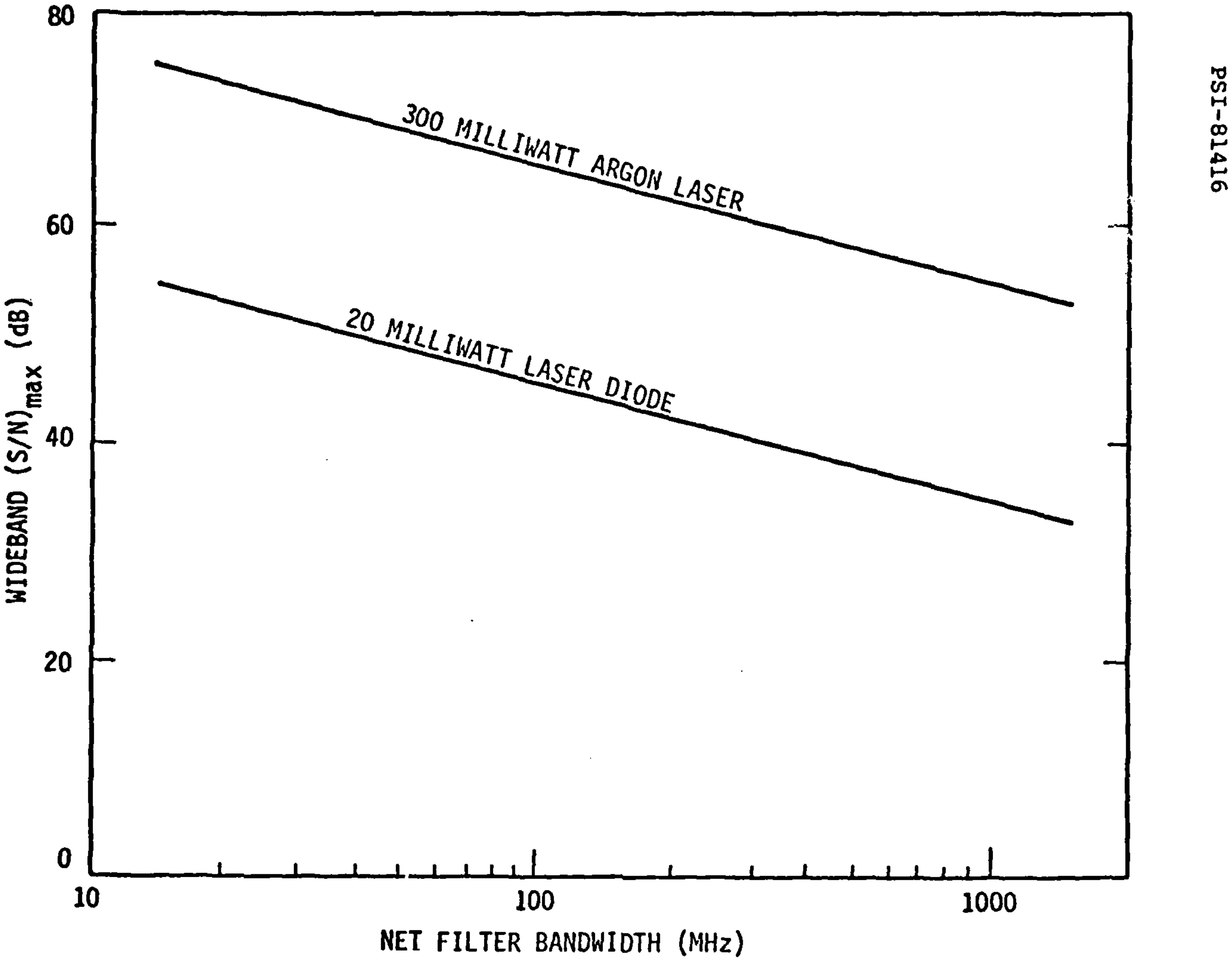


10 MHz/div

B. TWO-TONE RESPONSE

FIGURE A-5

MEASURED SIGNAL, NOISE AND INTERMODULATION LEVELS FOR AN OPTICAL EXCISOR.
THE SPECTRUM ANALYZER NOISE BANDWIDTH IS 30 kHz
AND THE NET OPTICAL EXCISOR BANDWIDTH IS 45 MHz



ASSUMPTIONS

1. TIME-BANDWIDTH PRODUCT OF 500
2. MAXIMUM ACOUSTO-OPTIC DIFFRACTION EFFICIENCY OF 10%
3. PIN PHOTODIODE DETECTOR

FIGURE A-6

THEORETICAL MAXIMUM WIDEBAND SIGNAL-TO-NOISE RATIO
VERSUS TOTAL BANDWIDTH FOR AN OPTICAL EXCISOR

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