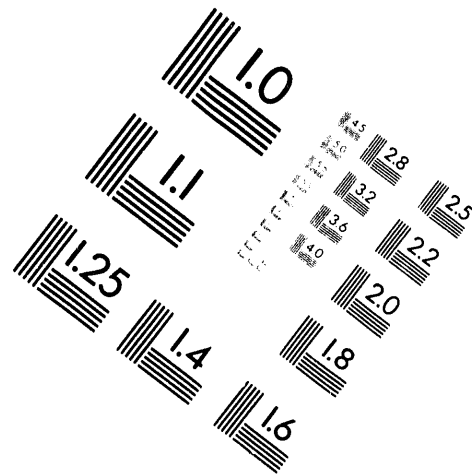
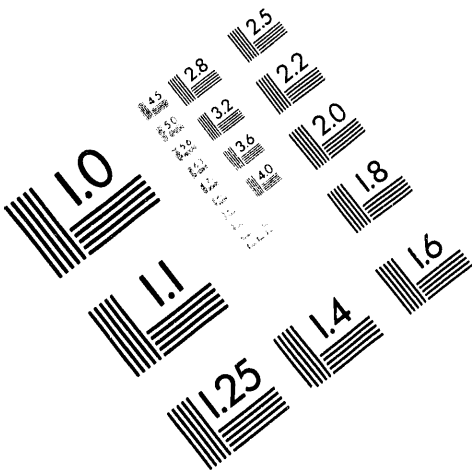




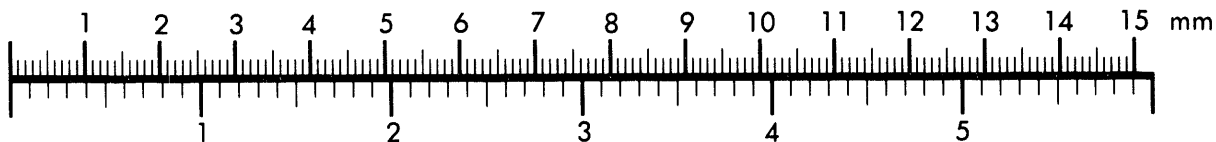
AIM

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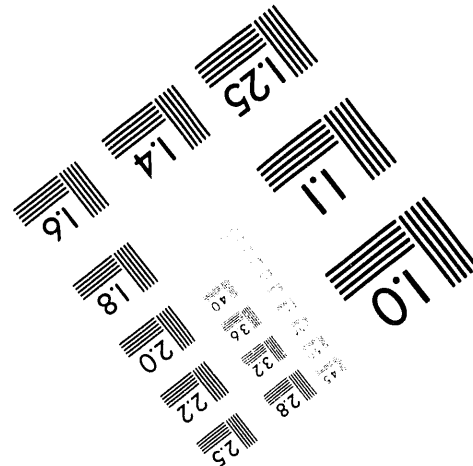
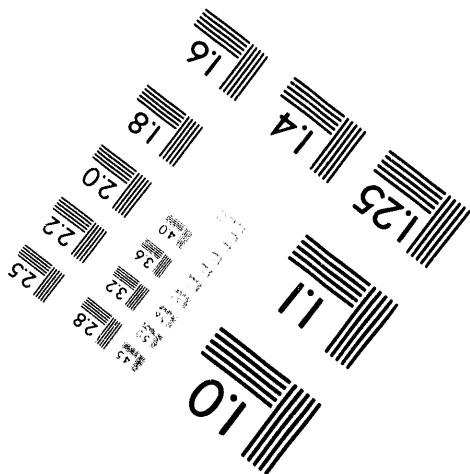
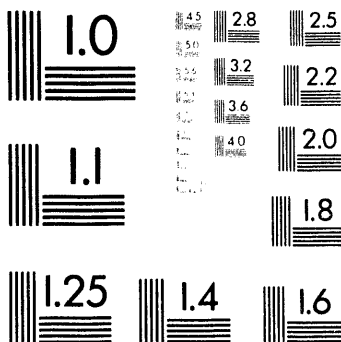
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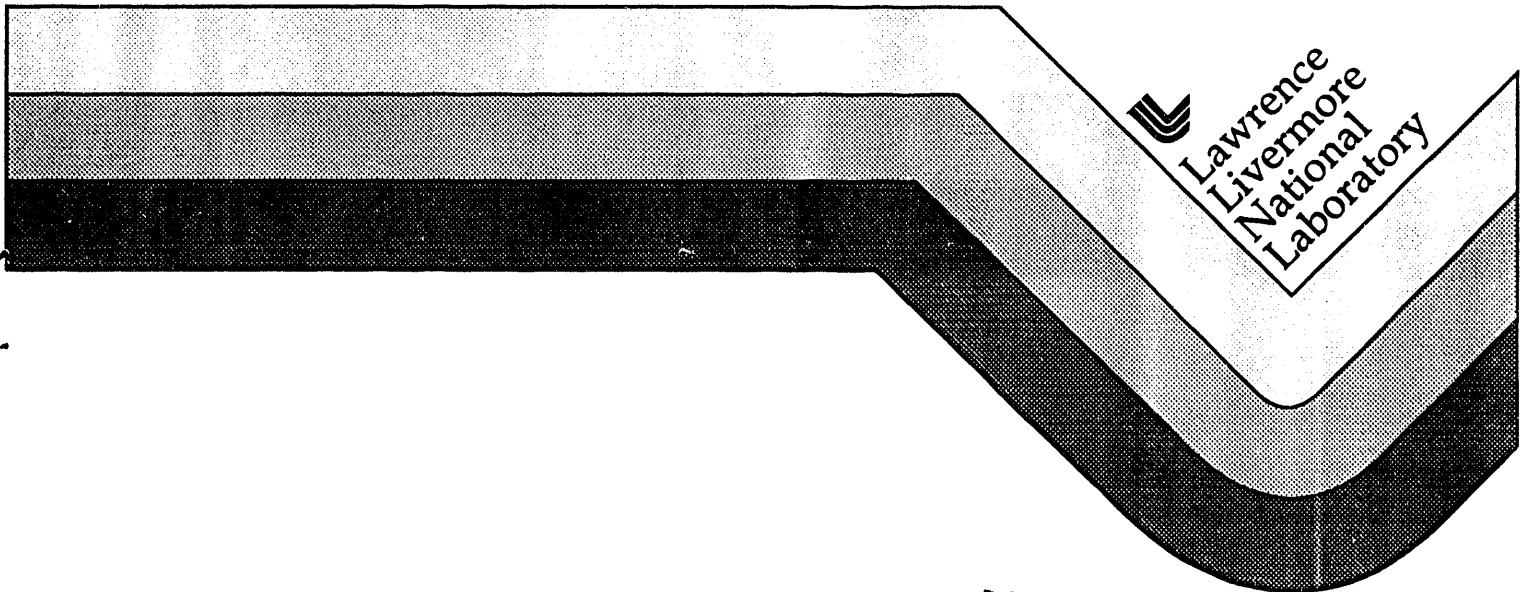
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**Final Report on Spectral Broadening by Cross-Phase
Modulation in Linearly Birefringent Optical Fibers**

C.-J. Chen
P. K. A. Wai
C. R. Menyuk

University of Maryland
Department of Electrical Engineering

December 1993



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Final Report on Spectral Broadening by Cross-Phase Modulation in Linearly Birefringent Optical Fibers

by

C.-J. Chen, P. K. A. Wai, and C. R. Menyuk

Department of Electrical Engineering, University of Maryland
Baltimore, MD 21228-5398

Abstract

Spectral widening by using the cross-phase modulation in a linearly birefringent optical fiber is investigated numerically. The coupled nonlinear Schrödinger equation that describes the wave propagation of each polarization in a birefringent optical fiber is discussed. Based on this equation, we generated computer simulations for different values of birefringence and dispersion. We found that a smooth output signal with intensity fluctuations of less than 10% and a spectral width of more than 50 Å is possible with low dispersion and low birefringence, e.g., $D = -10$ psec/nm-km and $\Delta n = 2 \times 10^{-5}$. We also found that the Raman effect does not play an significant role.

1 Introduction

Spectral widening by using the cross-phase modulation in a birefringent optical fiber has been proposed and carried out at Lawrence Livermore National Laboratory.^{1, 2} In these experiments, a broad band noisy pump beam and a narrow band smooth signal beam are launched into the two axes of a polarization maintaining fiber. Through cross-phase modulation, the intensity in one polarization axis of a fiber can affect the phase of the beam in the other axis, and vice versa. These phase variations induce a frequency shift which is then transformed into spectral broadening. When self- and cross-phase modulation dominate, the instantaneous frequency change is proportional to the time derivative of the optical intensity in the other axis. The spectral broadening of the signal beam which is in one axis depends on the statistical characteristics of the pump intensity, which is in the other axis, so that spectral broadening of the signal beam is proportional to the average intensity of the pump beam and the propagation distance. However, in most cases, complication arises because the signal beam changes shape as it propagates due to dispersion, birefringence, and the Raman effect. As a consequence, the signal beam develops undesirable intensity fluctuations.

In the interim report that we submitted in May, we showed preliminary simulation results, in which birefringence, dispersion, and the Raman effect are all taken into account. We demonstrated by a comparison between the simulations and experiments that the effective core area is 2.8 times the actual core area. We also noted that the Raman effect has only a minor effect on both spectral broadening and the location of the central frequency.

In this report, based on the knowledge that we had before, we describe a matrix of simulation results for dispersion $D = -5, -10, -20,$ and -40 psec/nm-km (normal dispersion) and birefringence $\Delta n = 5, 10, 20, 40,$ and 80×10^{-6} . For low dispersion and low birefringence, it is possible to obtain 50 Å over a short length of fiber. For example, a spectral width of 50 Å is obtained when $D = -10$ psec/nm-km, $\Delta n = 20 \times 10^{-6}$, and the fiber length is 6 m. We added the Raman effect to one run at each dispersion value and found no significant influence. For completeness, we include the formulation and results from the interim report.

2 Basic Equations and Normalizations

The equation that describes the wave evolution inside a birefringent optical fiber can be derived from Maxwell's equations by using the slowly varying envelope approximation. The two pulse profiles, U and V , in the two polarization axes of the birefringent optical fiber satisfy³

$$\begin{aligned} i\frac{\partial U}{\partial z} + ik'\frac{\partial U}{\partial t} - \frac{1}{2}k''\frac{\partial^2 U}{\partial t^2} + \frac{\omega_0 n_2}{c}(|U|^2 + B|V|^2)U &= 0, \\ i\frac{\partial V}{\partial z} + il'\frac{\partial V}{\partial t} - \frac{1}{2}l''\frac{\partial^2 V}{\partial t^2} + \frac{\omega_0 n_2}{c}(B|U|^2 + |V|^2)V &= 0, \end{aligned} \quad (1)$$

when the Raman effect can be ignored, where z is the propagation distance, t is time, ω_0 is the carrier angular frequency, and c is the speed of light. The dispersion relations for the two axes are $k(\omega)$ and $l(\omega)$ respectively and $k' = \partial k / \partial \omega|_{\omega_0}$, $l' = \partial l / \partial \omega|_{\omega_0}$, $k'' = \partial^2 k / \partial \omega^2|_{\omega_0}$, and $l'' = \partial^2 l / \partial \omega^2|_{\omega_0}$. We will discuss the relevant numerical values shortly. The parameter n_2 is the Kerr coefficient. Its numerical value is $n_2 = 3.2 \times$

$10^{-20} \text{ m}^2/\text{W}$.⁴ The cross-phase modulation is represented by B , which is $2/3$ for a linearly birefringent optical fiber.

The Raman effect at one frequency is described in terms of the pump intensity and the Stokes intensity. They have the following relationship

$$\frac{dI_s}{dz} = G_R I_p I_s, \quad (2)$$

where I_p and I_s are the pump and the Stokes intensities respectively. The coefficient G_R depends on the frequency difference between the pump and the Stokes waves and is proportional to the pump frequency, ω_p . For an optical fiber made of fused silica, G_R has a maximum value of $1.1 \times 10^{-13} \text{ m/W}$ at a frequency difference of 13.2 THz and a pump wavelength of $1 \mu\text{m}$. If the bandwidths of the pulses are much less than 13.2 THz, G_R can be approximated by a linear function in the frequency domain, which corresponds to a first derivative in the time domain.⁴ In such an approximation, $G_R = C_R f$, where f is the frequency difference and C_R is $8.3 \times 10^{-27} \text{ m-sec/W}$ from the measured quantities above. Note that in a birefringent fiber, the perpendicular Raman response has to be taken into account.⁵ In the slowly varying envelope approximation mentioned above, the Raman contributions are included by adding terms at the end of each sub-equation,

$$\begin{aligned} i \frac{\partial U}{\partial z} \Big|_{\text{Raman}} + \left(C_1 U \frac{\partial |U|^2}{\partial t} + C_2 U \frac{\partial |V|^2}{\partial t} + C_3 V \frac{\partial UV^*}{\partial t} \right) &= 0, \\ i \frac{\partial V}{\partial z} \Big|_{\text{Raman}} + \left(C_1 V \frac{\partial |V|^2}{\partial t} + C_2 V \frac{\partial |U|^2}{\partial t} + C_3 U \frac{\partial VU^*}{\partial t} \right) &= 0, \end{aligned} \quad (3)$$

where $C_1 = C_R/2$ is for the parallel Raman effect and C_2 and C_3 , whose values are both equal to $C_1/3$, are for the perpendicular Raman effect.⁶

The complete equation is the combination of Eq. (1) and Eq. (3). Normalization of the equation is convenient for doing numerical simulations. We carry out the normalization as follows. By setting new variables,

$$s = \frac{t}{T}, \quad \xi = \frac{z}{Z}, \quad u = \frac{U}{\sqrt{I}}, \quad v = \frac{V}{\sqrt{I}} \quad (4)$$

and choosing $I = c/\omega_0 n_2 Z$, $T = 1$ psec, and $Z = 1$ m, We obtain

$$\begin{aligned} i \frac{\partial u}{\partial \xi} + i\delta \frac{\partial u}{\partial s} + \epsilon \frac{\partial^2 u}{\partial s^2} + (|u|^2 + \frac{2}{3}|v|^2)u + c_1 u \frac{\partial |u|^2}{\partial s} + c_2 u \frac{\partial |v|^2}{\partial s} + c_3 v \frac{\partial uv^*}{\partial s} &= 0, \\ i \frac{\partial v}{\partial \xi} - i\delta \frac{\partial v}{\partial s} + \epsilon \frac{\partial^2 v}{\partial s^2} + (\frac{2}{3}|u|^2 + |v|^2)v + c_1 v \frac{\partial |v|^2}{\partial s} + c_2 v \frac{\partial |u|^2}{\partial s} + c_3 u \frac{\partial vu^*}{\partial s} &= 0, \end{aligned} \quad (5)$$

where $\delta = 1.67 \times 10^3 \Delta n$, and Δn is the difference between the refractive indices of the two polarizations. The parameter $\epsilon = 0.294 \times D$, where D is the chromatic dispersion measured in psec/nm-m. The intensity normalization I has a value of $5.24 \text{ W}/\mu\text{m}^2$. The Raman coefficients are given $c_1/3 = c_2 = c_3$ and $2\pi c_1 = 1.86 \times 10^{-2}$.⁶

We solve Eq. (5) using a second order accurate beam propagation method.⁷ Given the initial pulse profiles, we calculate their evolution according to Eq. (5). The output profiles are further analyzed to obtain the power, the peak power/average power, the central frequency, and the spectral width of each polarization. The broadband pump has a spectral width of 450 GHz, which corresponds to 2 psec variations in the time domain, and the number of sampling points in the time domain must be large enough to resolve these structures. It is not practical to simulate entire pulses, which have durations of 10 nsec. Instead, we simulate a time slice by using a time window of several hundred picoseconds.

3 Numerical Simulations (from the Interim Report)

In this section, we review the numerical simulations and the comparison with experiments previously described in the interim report. The emphasis in this section is upon determining the effective area of the experimental fiber and the importance of the Raman effect.

From the experimental results,^{1, 2} we find the parameters that are needed in the numerical simulations. The wavelength used is $\lambda_0 = 1.053 \mu\text{m}$. The refractive index difference used is $\Delta n = 6 \times 10^{-5}$, and the dispersion used is $D = -0.04 \text{ psec/nm-m}$. The pulse energy of the signal is $1 \mu\text{J}$ and the duration is 10 nsec. The broadband pulse has an energy of $5 \mu\text{J}$, a duration of 15 nsec, and a spectral width of 450 GHz. In the simulation of this broadband noisy pump beam, we assume a random phase relation for all the modes. The fiber core size is $4 \mu\text{m} \times 6 \mu\text{m}$, or $24 \mu\text{m}^2$. The optical intensity in each polarization can be obtained by calculating the ratio of pulse energy to pulse duration and then dividing by the effective core area, which is defined as

$$A_{\text{eff}} = \frac{(\int I dA)^2}{\int I^2 dA}, \quad (6)$$

where I is intensity and A is area.

The effective core area is roughly twice the actual core area,⁸ but the exact value must be determined empirically. To do so, we carried out a series of simulations in which the Raman effect is neglected, *i.e.*, $c_1 = c_2 = c_3 = 0$. Spectral broadening in both polarizations is then observed. As we increase the effective area relative to the

measured area, we find that the intensity decreases and, hence, the spectral broadening decreases. The best agreement with the experiments was found when $A_{\text{eff}} = 2.78 \times$ the core area. This can be seen by reference to Table 1, which summarizes all the simulations which were previously included in the interim report.

In the simulated results, the analyzed data is followed by the pulse profiles and spectra of both polarizations. In the analyzed data, we calculate at various propagation distances the pulse intensity (I_{tsy}), the peak intensity/average intensity (pk/avg), the central frequency (f_{cent}), and the spectral width (f_{width}). The definition of the last two quantities are:

$$f_{\text{cent}} = \frac{\int \omega |\tilde{u}(\omega)|^2 d\omega}{\int |\tilde{u}(\omega)|^2 d\omega}, \quad (7)$$

$$f_{\text{width}} = 2\sqrt{2\ln(2)} \left[\frac{\int \omega^2 |\tilde{u}(\omega)|^2 d\omega}{\int |\tilde{u}(\omega)|^2 d\omega} - (f_{\text{cent}})^2 \right]^{1/2}, \quad (8)$$

where $\tilde{u}(\omega)$ represents the Fourier transform of a certain pulse profile u . The factor in the spectral width is the ratio of the FWHM width to the variance of a Gaussian function.

Simulated results are attached at the end of the report in the Appendix. Set #1 corresponds to $A_{\text{eff}} = 2.78 \times$ the core area. As the pulses in each polarization propagate down the fiber, their spectral widths increase. At the beginning of the propagation, the signal pulse broadens rapidly and tends toward a limiting value. Its intensity becomes noisier as it propagates because of the dispersion. Additionally, the frequency centroids of the two polarizations shift apart because the two polarizations are bound together through cross-phase modulation and their frequency centroids shift in the

directions required to eliminate the velocity difference. The central frequency of the slow axis shifts down since in the normal dispersion regime lower frequencies travel faster. The pulse in the fast axis shifts correspondingly to higher frequency.

When the Raman effect is included in the simulations, the results are almost unchanged because the spectral widths of the pulses are small. The results are in Set #2 for the same parameters as in Set #1. A small fraction of power is transferred from the fast axis, which has a higher central frequency, to the slow axis as expected with the Raman effect, *i.e.*, the higher frequency component pumps the lower frequency one. We also notice some additional frequency downshifts in both polarizations. Again, this result is expected with the Raman effect.⁴

Twelve computer simulations using various effective areas, some of which include the Raman effect and some of which do not, are summarized in Table 1. For each simulation, we list the spectral widths as the fiber length increases. When the effective area equals $2.78 \times$ the actual area, the spectral broadening becomes comparable with the measured values. This value was determined by interpolation from runs 3 and 4 and was confirmed in run 5 in which the spectral widths are close to the experimental values. The measured values are obtained from the experimental data,^{1, 2} using $1 \text{ \AA} = 27 \text{ GHz}$ (at $\lambda = 1.053 \text{ \mu m}$). The Raman effect has only a slight effect as comparison of run nos. 2 and 5 to run nos. 3 and 6 shows. The attached Sets #1 and #2 correspond to run nos. 5 and 6 respectively. Three runs, nos. 7, 8, and 9, with effective areas 60, 96, and 120 \mu m^2 are included for reference. The dispersion of the fiber in run no. 10 is half of that of run no. 5 while the birefringence in run no. 11 is half of that

of run no. 5. All other parameters are the same as those of run no. 5. In run no. 12, both the dispersion and birefringence are half of that of run no. 5. For all the propagation distances in runs no. 10, 11, and 12, the spectral broadening is larger than the corresponding one in run no. 5. The spectral broadening also takes a longer distance to saturate when compare to that of run no. 5.

4 Numerical Simulations (New Results)

In this section, we describe the results which we have obtained since we submitted the interim report. The emphasis is upon determining the conditions under which it is possible to obtain 50 Å of spectral width.

We carried out a matrix of simulations with $D = -5, -10, -20,$ and -40 psec/nm-km (normal dispersion) and $\Delta n = 5, 10, 20, 40$ and 80×10^{-6} . We did four additional runs to check the impact of the Raman effect. In Table 2, we summarize these 24 runs of numerical simulation and list the output signal spectral widths. The effective core area in all these simulations is taken to be $66.72 \mu\text{m}^2$, which is adopted from the results of the interim report and close to the effective core areas of most optical fibers.

In these simulations, we also analyze on the fluctuations of the signal pulses. The ratio of the signal intensity variation to its average intensity (var/avg) is calculated for each simulation. The definition is

$$\text{var}/\text{avg} = \frac{(\langle |u(t)|^4 \rangle - \langle |u(t)|^2 \rangle^2)^{1/2}}{\langle |u(t)|^2 \rangle}, \quad (9)$$

where $\langle x \rangle = \int_{-x_1}^{x_1} x(t) dt / 2x_1$ and $2x_1$ is the window size of the simulation, which is 100 picoseconds. This ratio can be used as a measure of the fluctuation of the optical intensity.

We find that the signal spectral width decreases as birefringence increases under fixed dispersion. Since the walk-off effect increases for both polarizations at larger birefringence, the phase changes due to the cross phase modulation are relatively uniform because the noisy pump beam walks through the signal pulse. This averaging effect reduces the signal spectral width.

For fixed birefringence, spectral width decreases with increasing dispersion except when the birefringence is large ($\Delta = 80 \times 10^{-6}$). When dispersion is large, the change in shape of the optical beams due to dispersion becomes significant in both polarizations. The fluctuation in optical intensities also leads to a more uniform phase shift and hence reduces signal spectral width. However, high birefringence and therefore larger walk-off is expected to destroy the averaging effect of pulse shape fluctuation.

For the same spectral width, the signal beam is smoother at lower birefringence and lower dispersion. There are several instances in which the signal spectral widths exceed 50 Å, or 1350 Ghz, especially at low birefringence. At high birefringence, although 50 Å is reachable, the signal suffers from too much fluctuation. To obtain 1350 Ghz, the var/avg is 0.068 at 4 m in run no. 1, Table 2; while it is 0.524 at 8 m in run no. 16. Low dispersion and low birefringence improve the smoothness of the signal beam. In order to verify that the Raman effect has no impact on this results,

we included the Raman effect in several cases which are listed in Table 2 as runs 21–24.

The main difficulty at low birefringence is that it is difficult to maintain a high polarization extinction ratio. Theoretically, the polarization extinction ratio can be arbitrarily high if there are no defects and twists in the fiber. Extinction ratios larger than 10 dB are possible over 100 m for birefringence as low as 1×10^{-5} with careful handling of the fibers in the experiments so that they are free of twist and stress.⁹ Since the fiber length used is only a few meters, the birefringence may be decreased further while still maintaining a good extinction ratio.

5 Conclusions

We have formulated and studied numerically spectral broadening of optical pulses by using the cross phase modulation of a birefringent optical fiber. With low dispersion and low birefringence, one can obtain a smooth signal output with a spectral width of more than 50 Å. To do so, while maintaining a good polarization extinction ratio, one must use high quality fibers and handle them carefully.

Acknowledgement

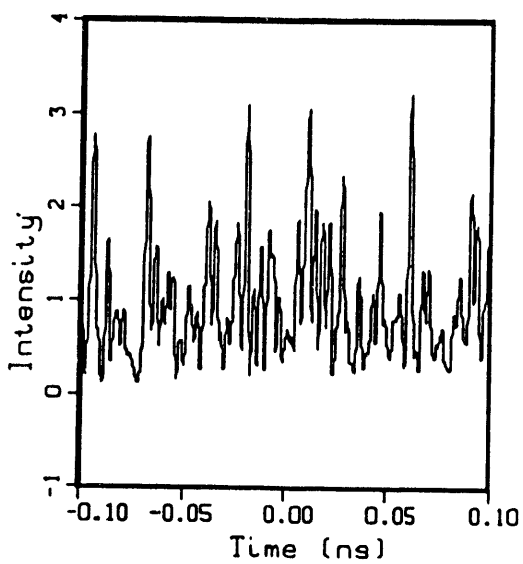
The authors would like to thank Dr. R. H. Stolen of AT&T Bell Laboratories for discussing with us achievable fiber parameters.

References

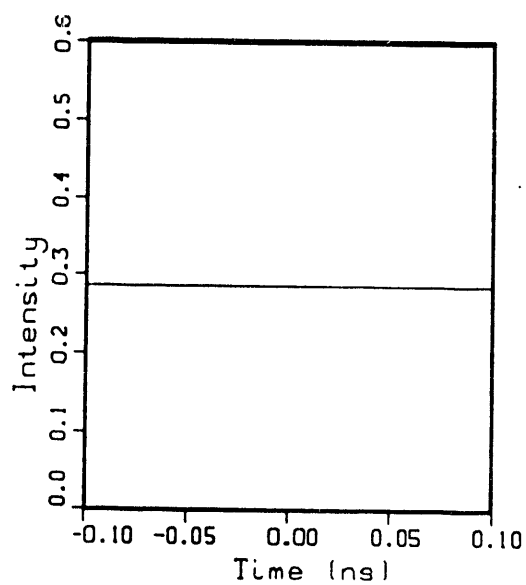
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Run No.	effective area μm^2	Raman included	Propagation distance (m)	Spectral width of the signal (GHz)	Comment	
1	24	No	1.5	1091.0		
			3.0	1372.9		
			4.5	1604.6		
			6.0	1727.4		
			7.5	1872.2		
			9.0	2005.1		
			10.5	2072.7		
2	48	No	1.5	707.2		
			3.0	959.4		
			4.5	1063.9		
			6.0	1151.4		
			7.5	1293.9		
			9.0	1430.7		
			10.5	1489.9		
3	48	Yes	1.5	707.5	Compared with run no. 2, the Raman effect does not significantly change the spectral widths.	
			3.0	960.2		
			4.5	1065.6		
			6.0	1159.5		
			7.5	1312.2		
			9.0	1458.1		
			10.5	1528.4		
4	72	No	1.5	500.0		
			3.0	757.7		
			4.5	844.3		
			6.0	885.9		
			7.5	934.1		
			9.0	1000.4		
			10.5	1074.8		
5	66.72	No	1.5	535.1		
			3.0	793.9		811.7 GHz (Measured)
			4.5	882.7		947.0 GHz (Measured)
			6.0	939.9		
			7.5	1036.5		1217.5 GHz (Measured)
			9.0	1106.9		
			10.5	1206.3		
6	66.72	Yes	1.5	535.2	Again, the spectral widths are not significantly changed by the Raman effect.	
			3.0	794.6		
			4.5	883.3		
			6.0	940.0		
			7.5	1038.5		
			9.0	1113.6		
			10.5	1220.9		
12.0	1325.8					

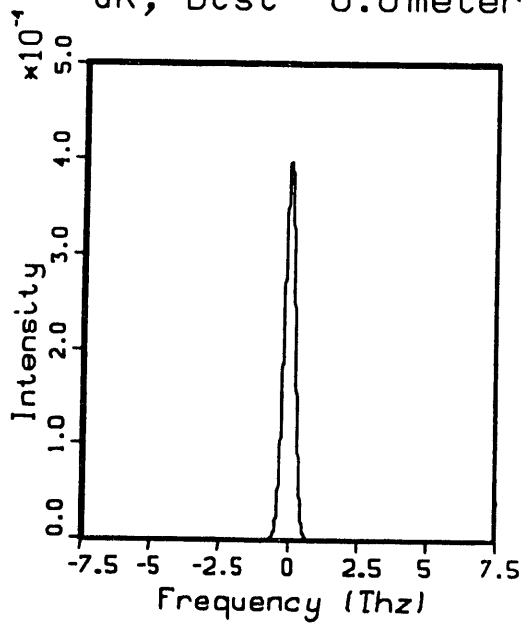
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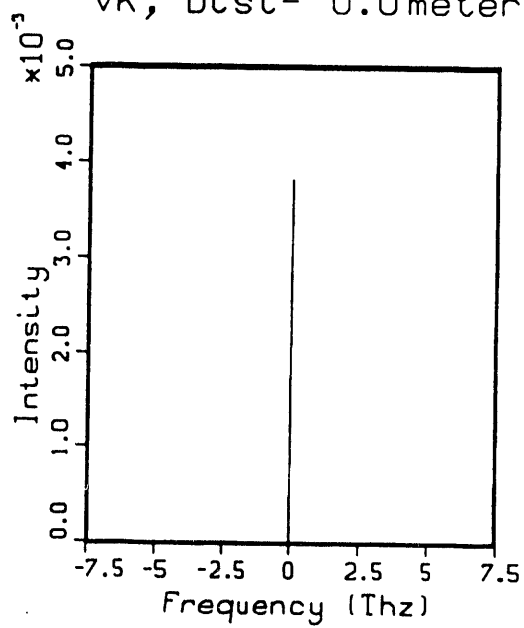
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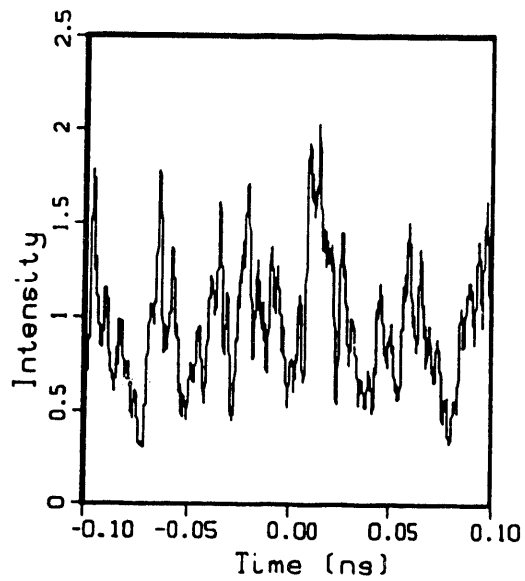
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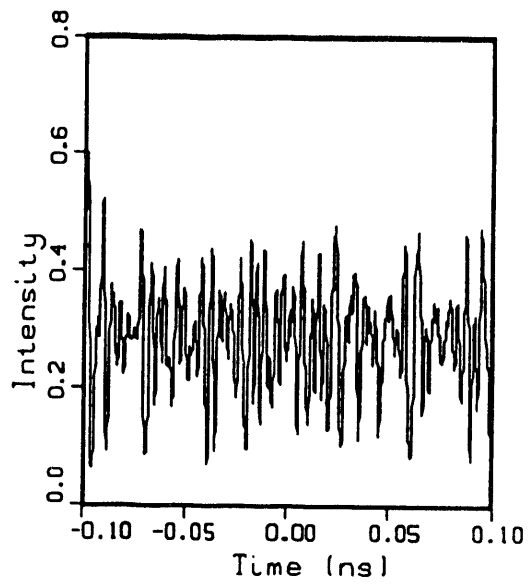
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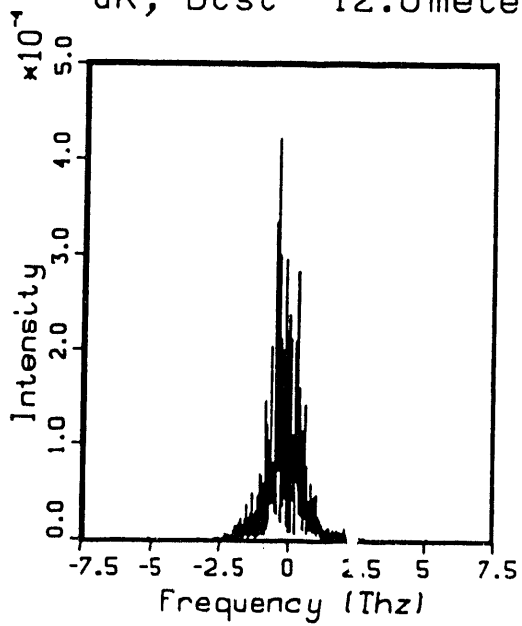
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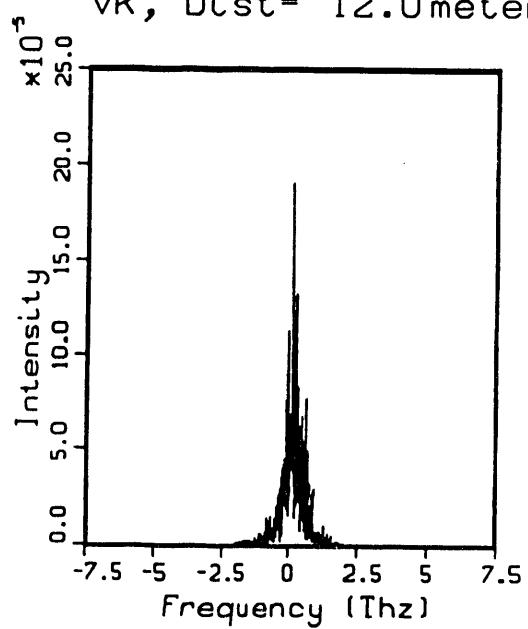
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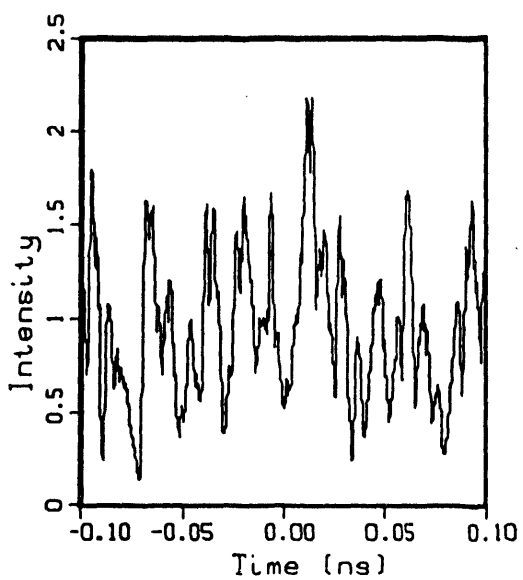
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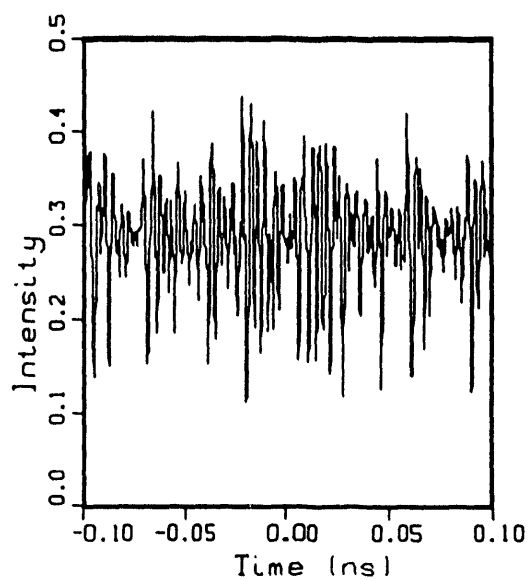
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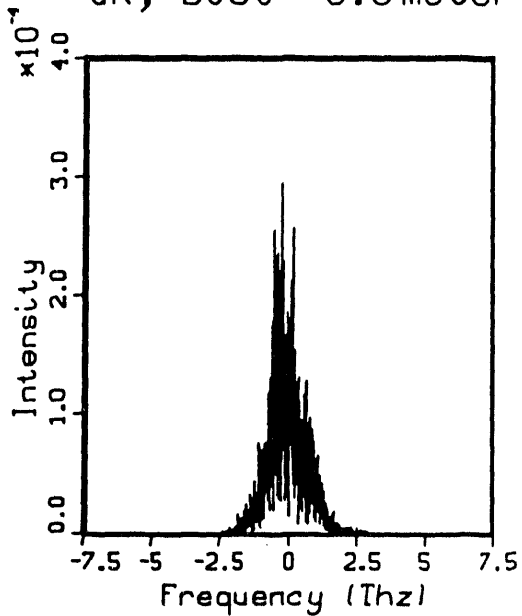
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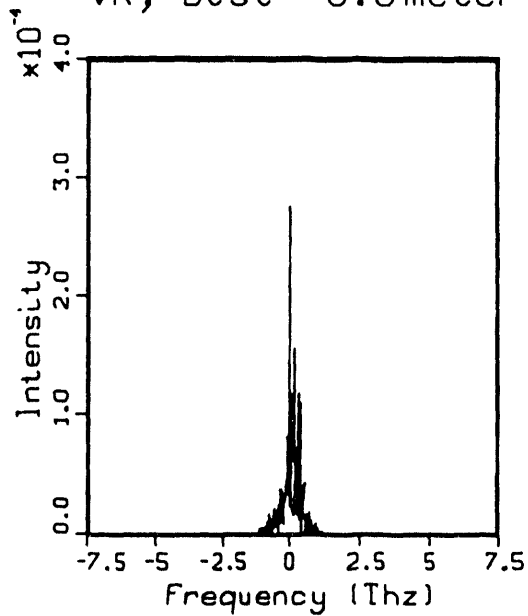
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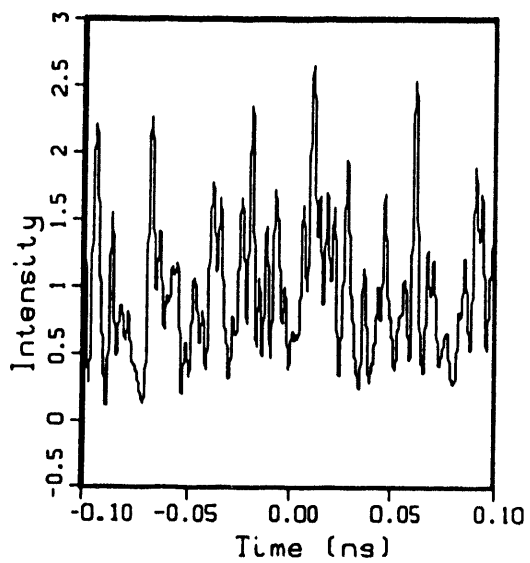
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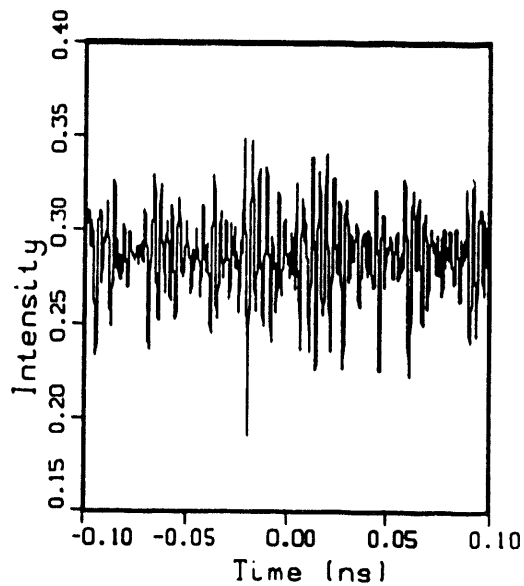
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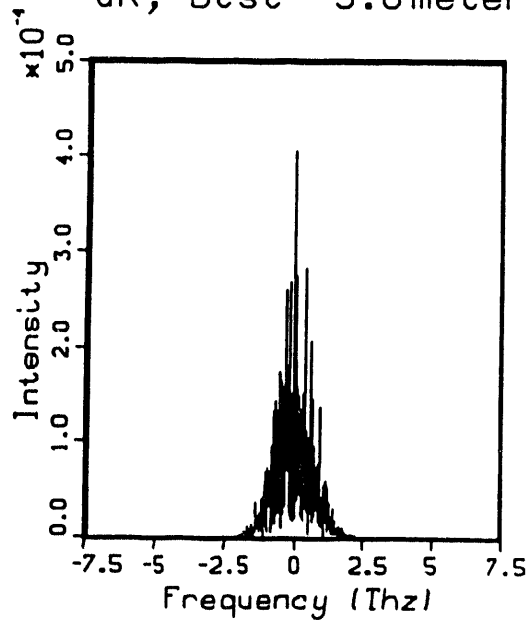
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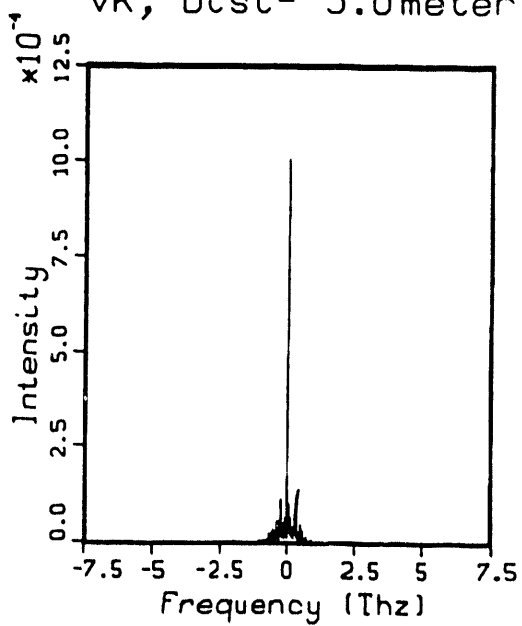
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uk, Dist= 3.0meter



vk, Dist= 3.0meter



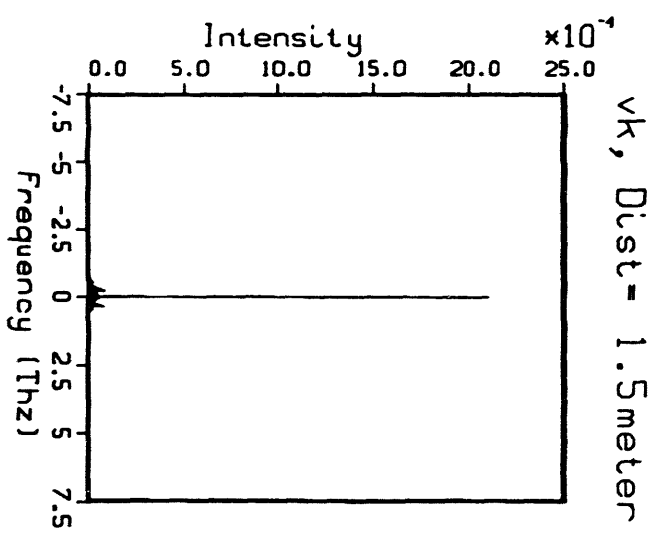
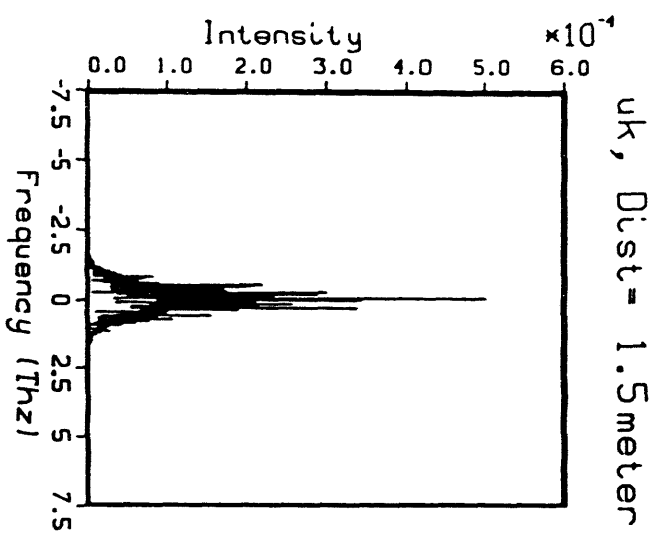
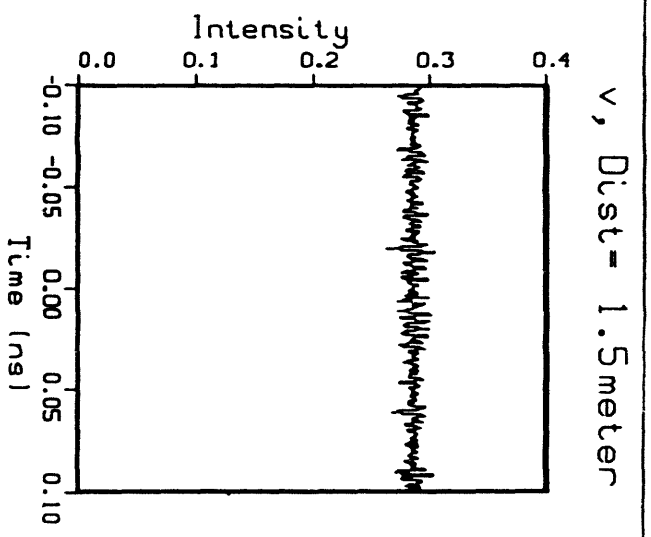
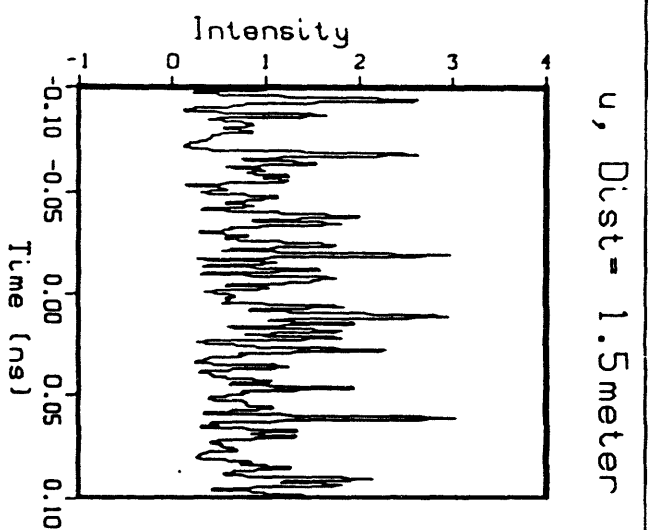


Table continued

Run No.	effective area μm^2	Raman included	Propagation distance (m)	Spectral width of the signal (GHz)	Comment
7	60	No	1.5	588.6	
			3.0	859.6	
			4.5	953.6	
			6.0	1031.0	
			7.5	1142.9	
8	96	No	9.0	1232.2	
			10.5	1345.1	
			12.0	1455.1	
			1.5	383.2	
			3.0	597.9	
9	120	No	4.5	679.5	
			6.0	712.3	
			7.5	757.9	
			9.0	811.3	
			10.5	856.4	
10	66.72	No	10.5	709.3	Dispersion is half the amount of run no. 5.
			12.0	745.5	
			1.5	311.1	
			3.0	498.0	
			4.5	576.1	
11	66.72	No	6.0	606.2	
			7.5	633.5	
			9.0	675.2	
			10.5	709.3	
			12.0	745.5	
12	66.72	No	6.0	606.2	Birefringence is half the amount of run no. 5.
			7.5	633.5	
			9.0	675.2	
			10.5	709.3	
			12.0	745.5	
12	66.72	No	1.5	545.8	Both dispersion and birefringence are half the amount of run no. 5.
			3.0	852.2	
			4.5	1022.9	
			6.0	1187.0	
			7.5	1300.9	
12	66.72	No	9.0	1375.1	
			10.5	1427.8	
			12.0	1477.8	
			1.5	576.5	
			3.0	980.6	
12	66.72	No	4.5	1199.0	
			6.0	1328.6	
			7.5	1434.5	
			9.0	1583.0	
			10.5	1756.9	
12	66.72	No	12.0	1901.3	

Table 1: Summary of the computer simulations in the interim report

Run No.	D (psec/nm-km)/ Δn ($\times 10^{-6}$)	Raman	Propagation distance (m)	Spectral width (GHz)/ var/avg	Comment
1	-5/5	No	2.0	708.4/0.0180	≈ 50 A, smoothest > 50 A
			4.0	1300.4/0.0675	
			6.0	1734.3/0.1438	
			8.0	2002.7/0.2440	
			10.0	2190.2/0.3377	
			12.0	2443.5/0.4043	
2	-5/10	No	2.0	707.4/0.0179	> 50 A
			4.0	1293.9/0.0671	
			6.0	1714.8/0.1422	
			8.0	1959.4/0.2386	
			10.0	2104.5/0.3293	
			12.0	2249.5/0.4011	
3	-5/20	No	2.0	703.7/0.0178	> 50 A
			4.0	1267.9/0.0658	
			6.0	1643.0/0.1352	
			8.0	1834.3/0.2182	
			10.0	1925.2/0.3022	
			12.0	1986.7/0.3712	
4	-5/40	No	2.0	688.7/0.0175	> 50 A
			4.0	1172.3/0.0607	
			6.0	1414.9/0.1141	
			8.0	1501.3/0.1670	
			10.0	1539.8/0.2145	
			12.0	1642.1/0.2563	
5	-5/80	No	2.0	632.5/0.0160	
			4.0	889.3/0.0457	
			6.0	904.9/0.0699	
			8.0	889.4/0.0880	
			10.0	890.8/0.1040	
			12.0	881.5/0.1173	

Run No.	D (psec/nm-km)/ $\Delta n (\times 10^{-6})$	Raman	Propagation distance (m)	Spectral width (GHz)/ var/avg	Comment
6	-10/5	No	2.0	687.0/0.0350	> 50 Å
			4.0	1183.4/0.1284	
			6.0	1462.4/0.2653	
			8.0	1665.6/0.3783	
			10.0	1948.0/0.4418	
			12.0	2150.1/0.4764	
7	-10/10	No	2.0	686.1/0.0350	> 50 Å
			4.0	1178.0/0.1278	
			6.0	1441.6/0.2622	
			8.0	1634.7/0.3735	
			10.0	1819.8/0.4395	
			12.0	1987.0/0.4755	
8	-10/20	No	2.0	682.5/0.0348	> 50 Å
			4.0	1154.9/0.1251	
			6.0	1381.0/0.2493	
			8.0	1487.0/0.3611	
			10.0	1577.2/0.4464	
			12.0	1672.2/0.4964	
9	-10/40	No	2.0	668.3/0.0341	> 50 Å
			4.0	1072.6/0.1152	
			6.0	1220.7/0.2121	
			8.0	1268.7/0.3006	
			10.0	1323.2/0.3654	
			12.0	1424.1/0.4062	
10	-10/80	No	2.0	615.8/0.0314	
			4.0	837.0/0.0881	
			6.0	859.4/0.1354	
			8.0	884.9/0.1711	
			10.0	920.9/0.1965	
			12.0	927.3/0.2133	

Run No.	D (psec/nm-km)/ Δn ($\times 10^{-6}$)	Raman	Propagation distance (m)	Spectral width (GHz)/ var/avg	Comment
11	-20/5	No	2.0	650.0/0.0672	> 50 Å
			4.0	1016.7/0.2355	
			6.0	1222.3/0.3925	
			8.0	1491.0/0.4654	
			10.0	1712.8/0.5050	
			12.0	1838.8/0.5375	
12	-20/10	No	2.0	649.5/0.0671	> 50 Å
			4.0	1010.4/0.2345	
			6.0	1222.3/0.3871	
			8.0	1474.3/0.4604	
			10.0	1663.8/0.4907	
			12.0	1823.1/0.5169	
13	-20/20	No	2.0	646.2/0.0688	> 50 Å
			4.0	988.7/0.2295	
			6.0	1160.1/0.3751	
			8.0	1314.6/0.4459	
			10.0	1428.0/0.4895	
			12.0	1442.1/0.5293	
14	-20/40	No	2.0	633.3/0.0655	> 50 Å
			4.0	922.3/0.2115	
			6.0	1004.9/0.3517	
			8.0	1087.4/0.4375	
			10.0	1227.5/0.4669	
			12.0	1332.2/0.5011	
15	-20/80	No	2.0	585.8/0.0604	
			4.0	752.3/0.1647	
			6.0	793.9/0.2481	
			8.0	872.7/0.3050	
			10.0	960.5/0.3385	
			12.0	1009.2/0.3634	

Run No.	D (psec/nm-km)/ $\Delta n (\times 10^{-6})$	Raman	Propagation distance (m)	Spectral width (GHz)/ var/avg	Comment
16	-40/5	No	2.0	592.1/0.1257	> 50 Å
			4.0	848.4/0.3609	
			6.0	1078.1/0.4815	
			8.0	1290.6/0.5239	
			10.0	1382.7/0.5744	
			12.0	1432.1/0.5954	
17	-40/10	No	2.0	591.3/0.1256	> 50 Å
			4.0	846.8/0.3586	
			6.0	1095.7/0.4704	
			8.0	1307.9/0.5216	
			10.0	1385.4/0.5637	
			12.0	1387.5/0.5843	
18	-40/20	No	2.0	588.3/0.1251	> 50 Å
			4.0	835.1/0.3509	
			6.0	1062.1/0.4562	
			8.0	1251.9/0.5017	
			10.0	1332.4/0.5385	
			12.0	1357.8/0.5534	
19	-40/40	No	2.0	577.1/0.1226	
			4.0	775.3/0.3300	
			6.0	906.3/0.4343	
			8.0	977.1/0.5000	
			10.0	1018.9/0.5630	
			12.0	1050.8/0.5941	
20	-40/80	No	2.0	536.5/0.1134	
			4.0	649.4/0.2813	
			6.0	743.6/0.3792	
			8.0	855.6/0.4344	
			10.0	913.6/0.4830	
			12.0	988.3/0.5074	

Run No.	D (psec/nm-km)/ $\Delta n (\times 10^{-6})$	Raman	Propagation distance (m)	Spectral width (GHz)/ var/avg	Comment
21	-5/20	Yes	2.0	703.8/0.0174	Compared with run no. 3 in this Table.
			4.0	1268.4/0.0603	
			6.0	1642.9/0.1195	
			8.0	1833.9/0.1870	
			10.0	1924.6/0.2537	
			12.0	2000.6/0.3088	
22	-10/80	Yes	2.0	615.6/0.0283	Compared with run no. 10 in this Table.
			4.0	837.5/0.0751	
			6.0	866.2/0.1175	
			8.0	909.8/0.1574	
			10.0	961.6/0.1878	
			12.0	977.4/0.2104	
23	-20/5	Yes	2.0	650.2/0.0673	Compared with run no. 11 in this Table.
			4.0	1016.5/0.2352	
			6.0	1229.6/0.3928	
			8.0	1524.4/0.4639	
			10.0	1755.9/0.5018	
			12.0	1863.0/0.5338	
24	-40/40	Yes	2.0	576.8/0.1214	Compared with run no. 19 in this Table.
			4.0	775.8/0.3240	
			6.0	907.5/0.4216	
			8.0	979.8/0.4846	
			10.0	1026.3/0.5435	
			12.0	1056.8/0.5780	

Table 2: A summary of computer simulation of different birefringence and dispersion

APPENDIX

Set #1

```

fper = 0.00050      length(m) =12.00000
xl(ns) = 0.10000
fm(m) = 1.50000
dn = 0.00006      B = 0.66667
dispersion(ps/nm/m) = -0.4000E-01
pump eng(uJ) = 5.0000
pump duration(ns) = 15.0000
pump spectral width(Ghz) =450.0000
signal eng(uJ) = 1.0000
signal duration(ns) = 10.0000
effective area(um**2) = 66.7200
amask = 0.0000
fmask = 1.0000
plotting parameters:
n=2048
xres= 2.000
xkres= 0.5000

```

u: the slow axis (broad band noise)

Dist (m)	Itsy (W/um**2)	pk/avg	fcent (Ghz)	fwidth (Ghz)
0.00	4.9960	5.2167	0.0071	449.9909
1.50	4.9960	3.8627	-0.6011	1161.0409
3.00	4.9960	2.8578	-3.8512	1652.5645
4.50	4.9960	3.5717	-8.5691	1822.3330
6.00	4.9960	3.8709	-19.4317	1855.1887
7.50	4.9960	3.4742	-32.9123	1873.1374
9.00	4.9960	3.4022	-48.5109	1901.5847
10.50	4.9960	3.5462	-63.3829	1910.1126
12.00	4.9960	2.9527	-74.6728	1913.9610

v: the fast axis (signal)

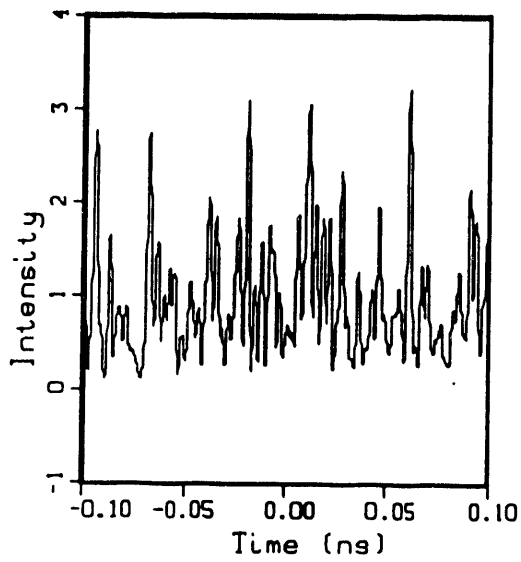
Dist (m)	Itsy (W/um**2)	pk/avg	fcent (Ghz)	fwidth (Ghz)	WIDTH_EXP (Ghz)
0.00	1.4988	1.0000	0.0000	0.0000	
1.50	1.4988	1.3417	1.9546	535.0502	
3.00	1.4988	2.2582	12.4524	793.8592	811.7
4.50	1.4988	3.4204	23.4915	882.6691	
6.00	1.4988	3.6421	39.3792	939.8679	947.0
7.50	1.4988	3.2122	61.5847	1036.4561	
9.00	1.4988	3.7110	93.6783	1106.9096	
10.50	1.4988	4.0298	122.4575	1206.2636	1217.5
12.00	1.4988	3.9456	151.7978	1302.6926	

Parameter values :

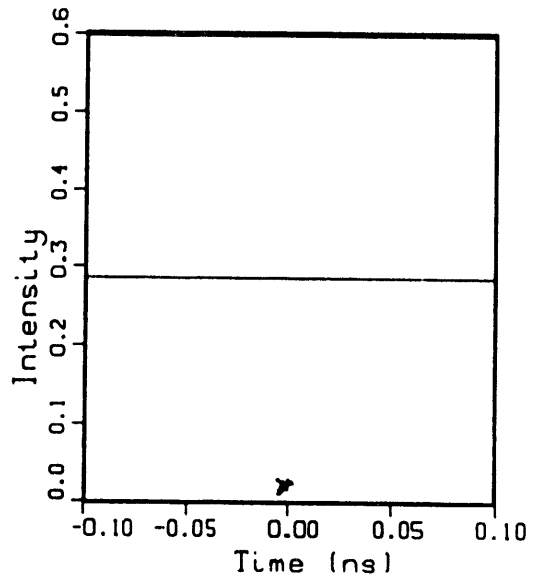
```
fpar = 0.0005000
length(m) = 12.000
xl(ns) = 0.1000
fm(m) = 1.5000
dn = 0.0000600
B = 0.6667
dpsn(ps/nm/m) --0.0400
pmpeng(vJ) = 5.0000
pmpdur(ns) = 15.000
pmpspwid(Ghz) = 450.00
sigeng(vJ) = 1.0000
sigdur(ns) = 10.000
aeff(umxx2) = 66.720
amask = 0.0000
fmask = 1.0000
n = 2048
xres(ps) = 2.0000
xkres(R) = 0.5000
```

!! Intensities, i.e., cabs(X)**2, are plotted !!

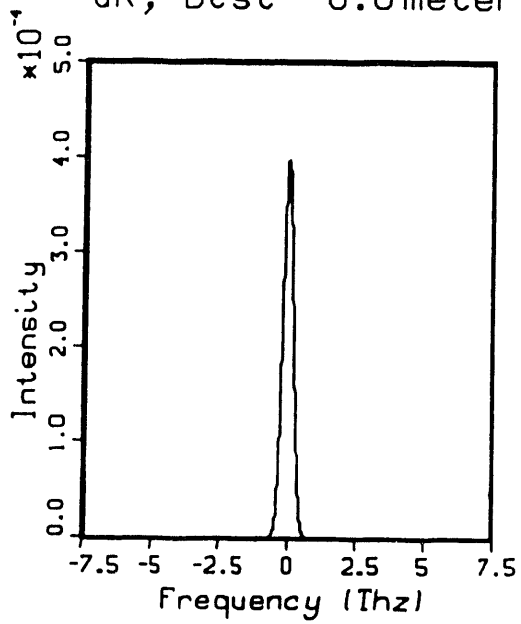
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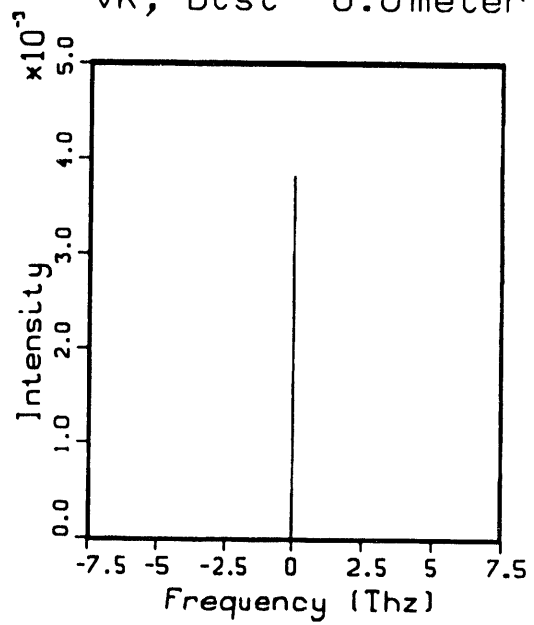
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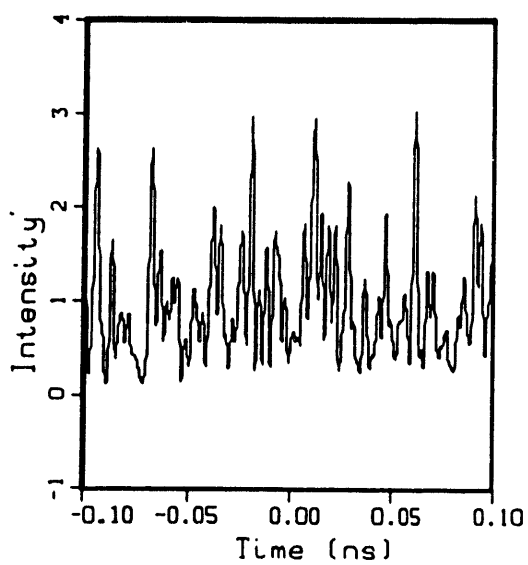
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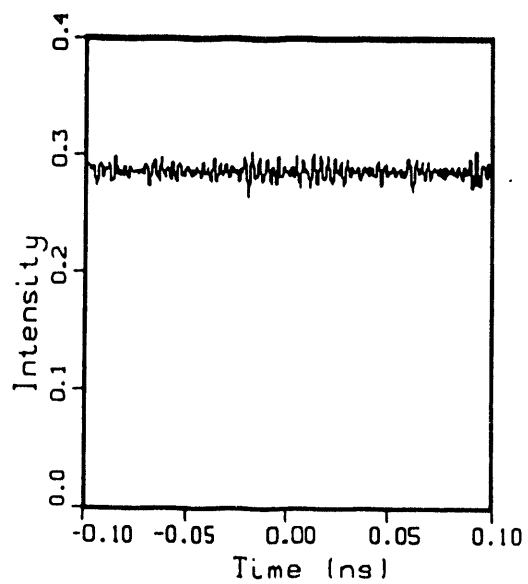
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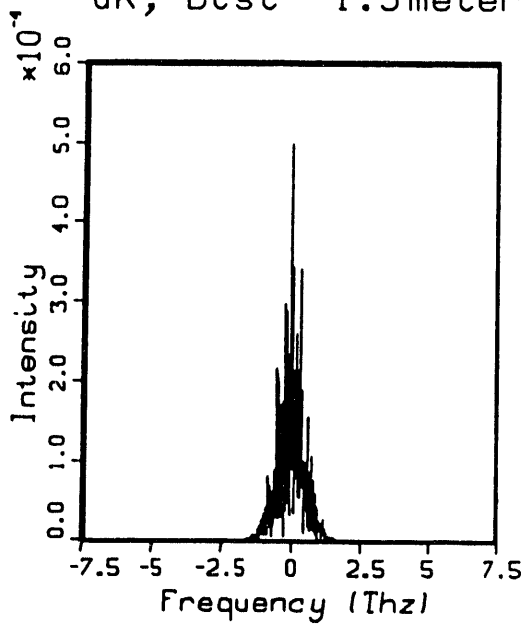
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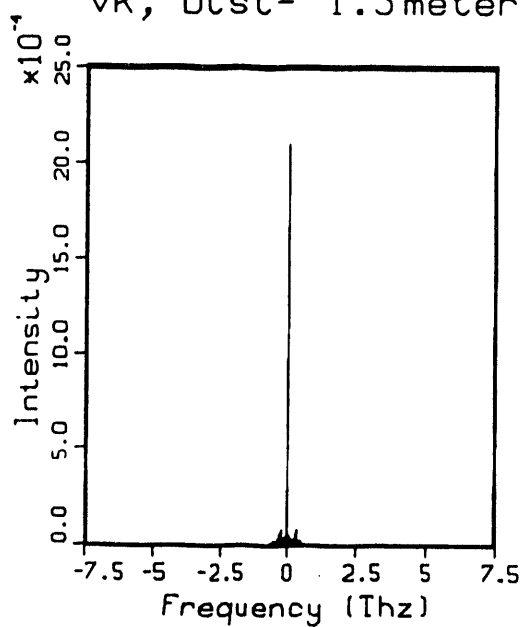
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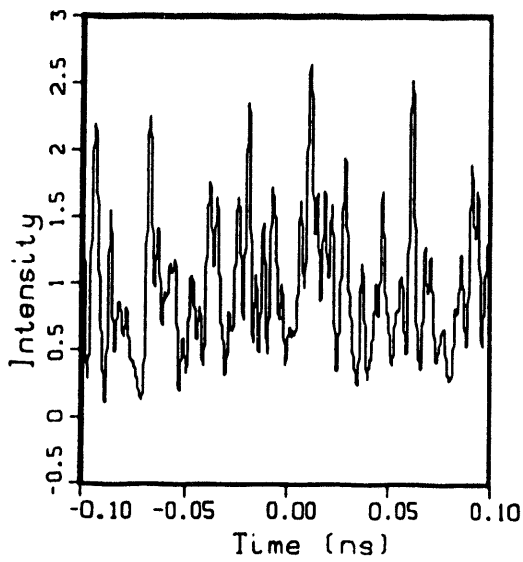
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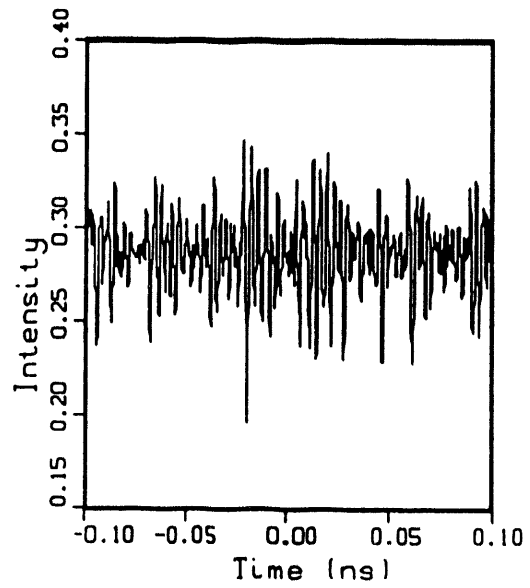
vk, Dist= 1.5meter



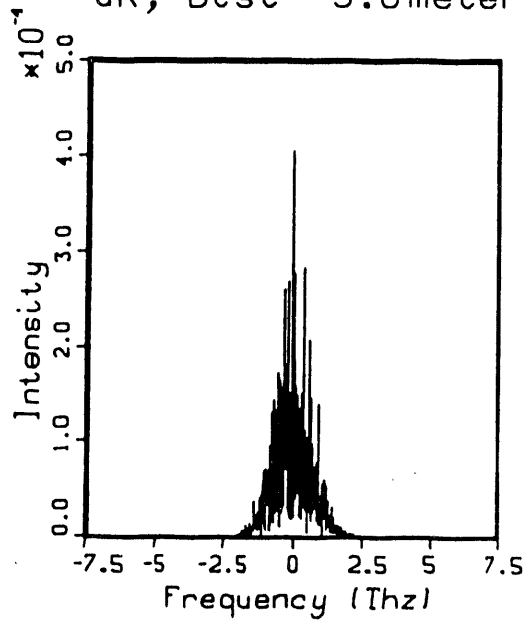
u, Dist= 3.0meter



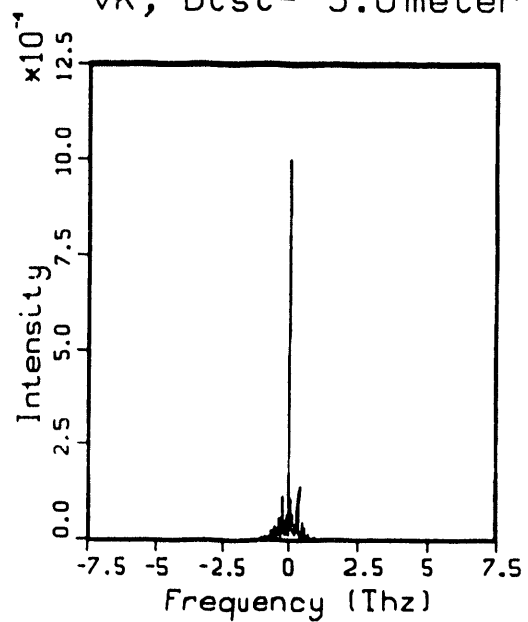
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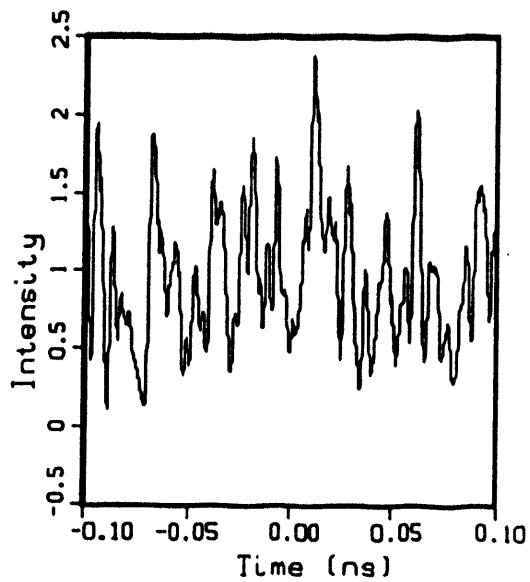
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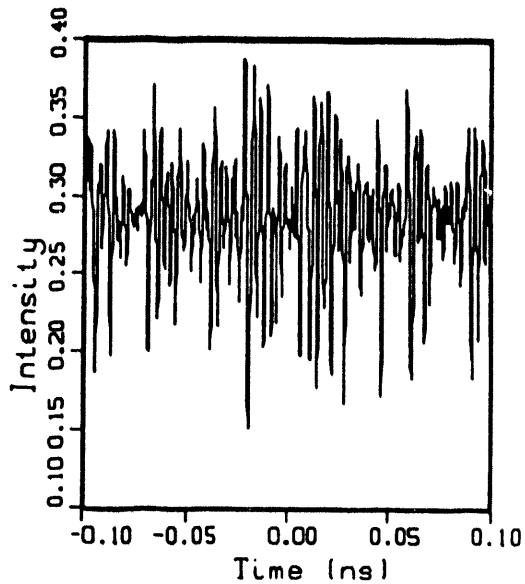
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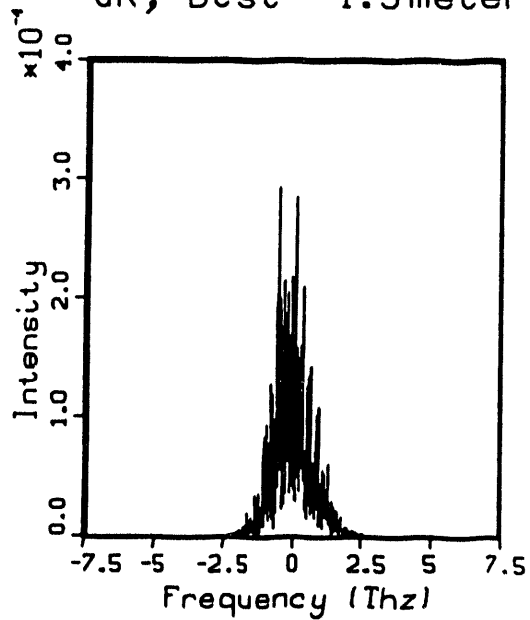
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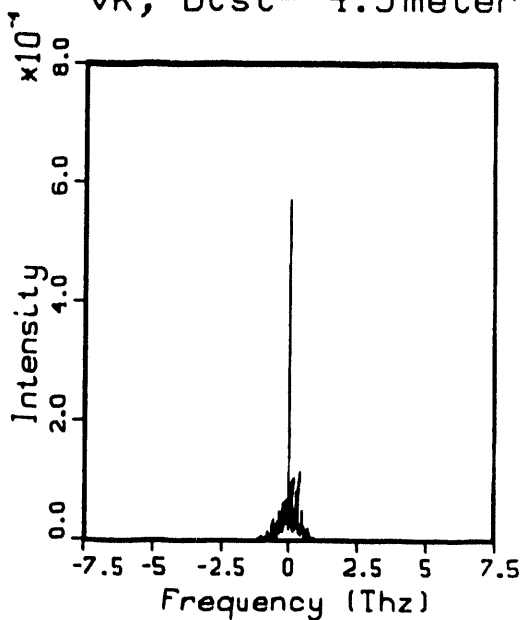
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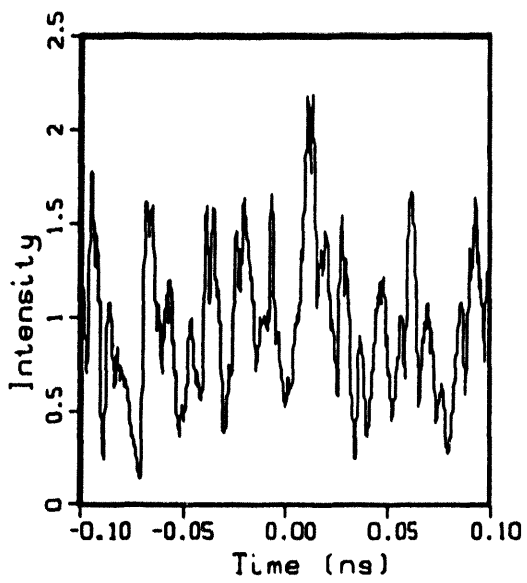
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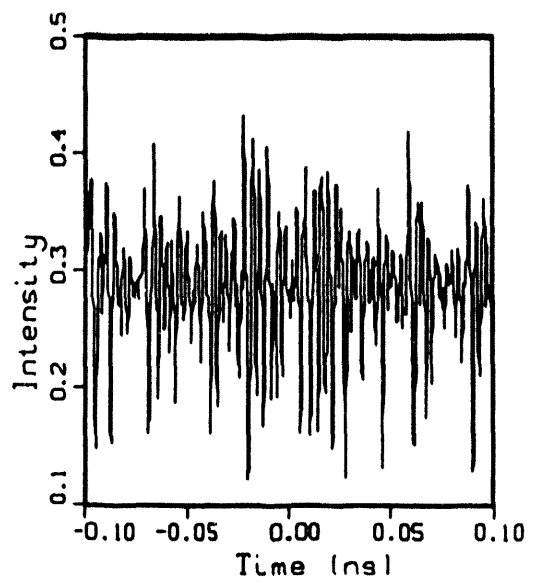
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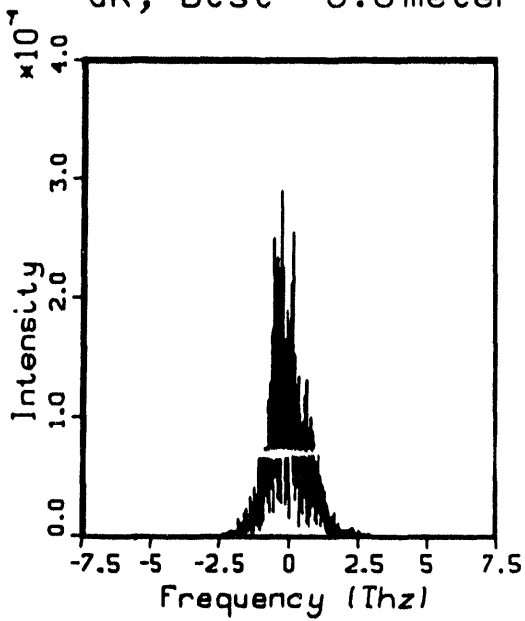
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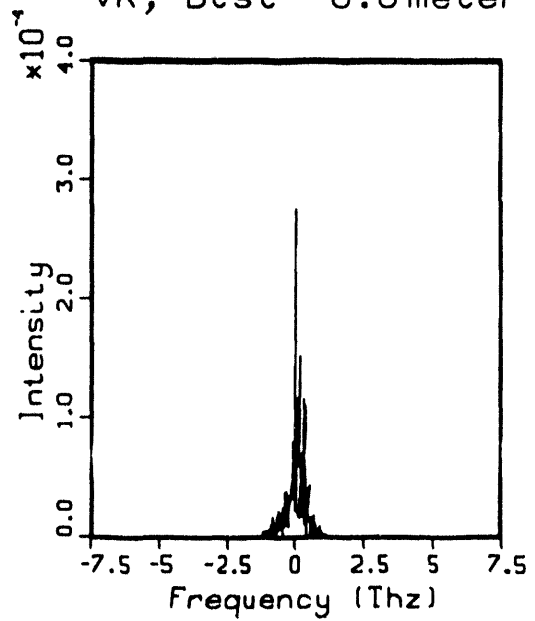
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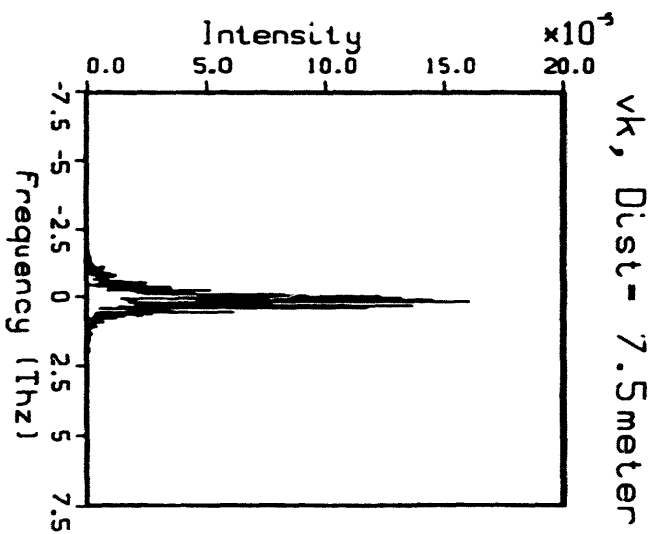
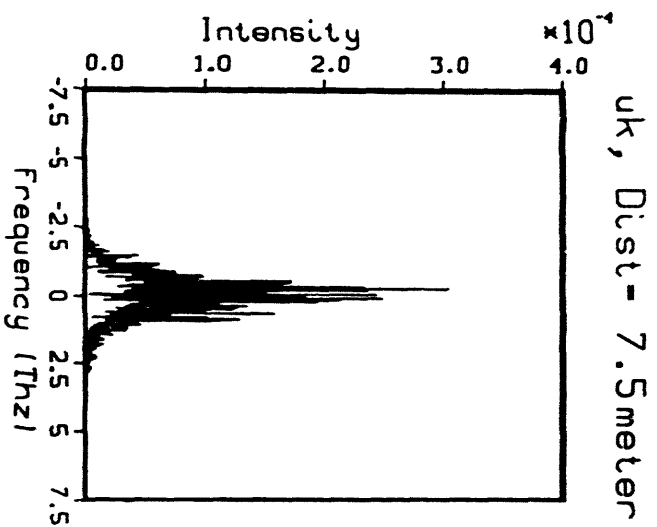
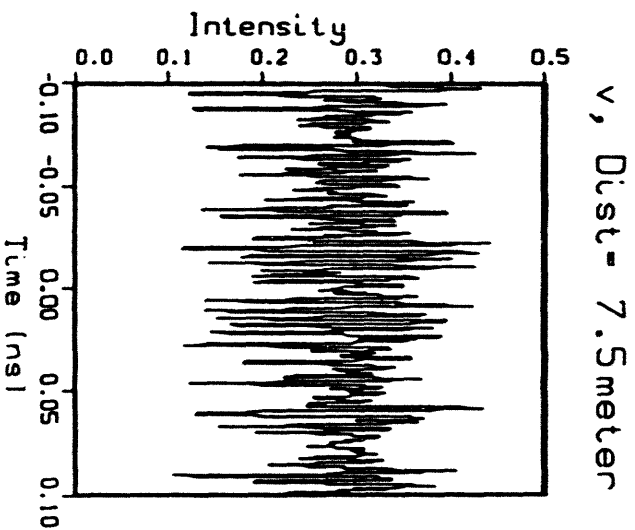
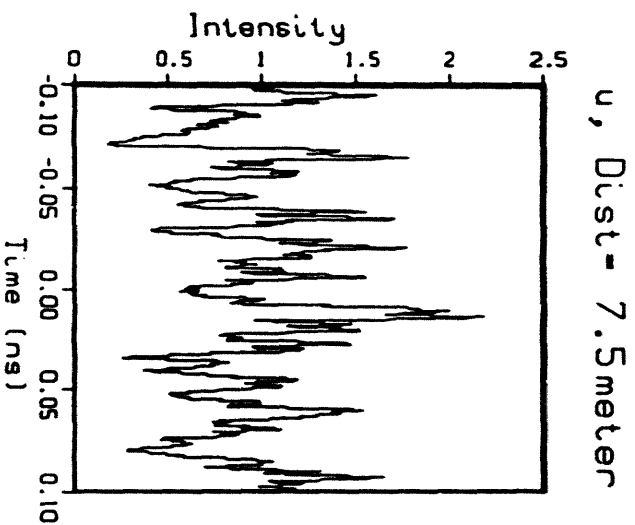


uk, Dist- 6.0meter

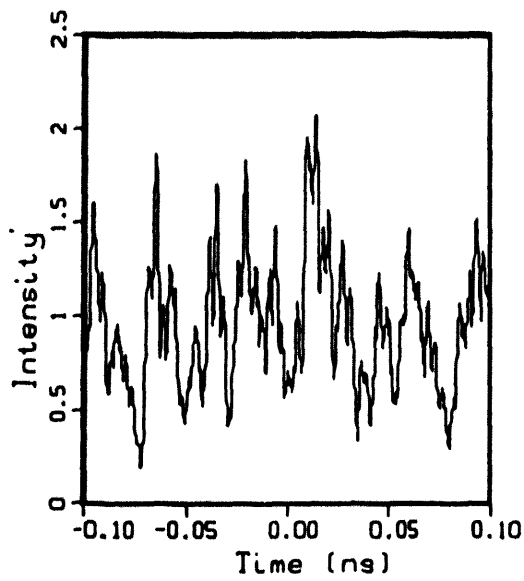


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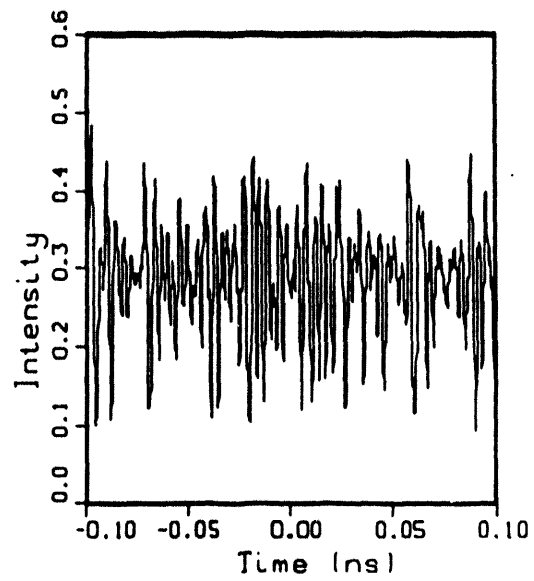




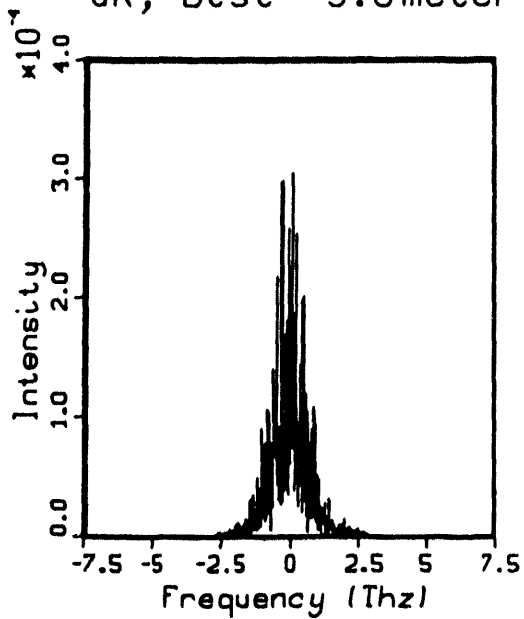
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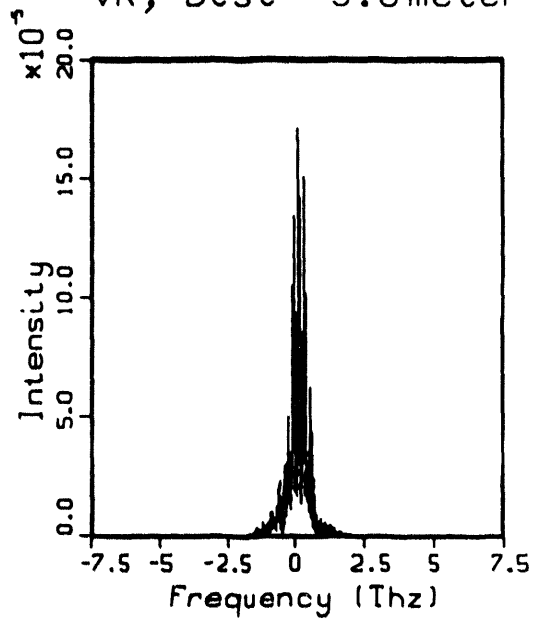
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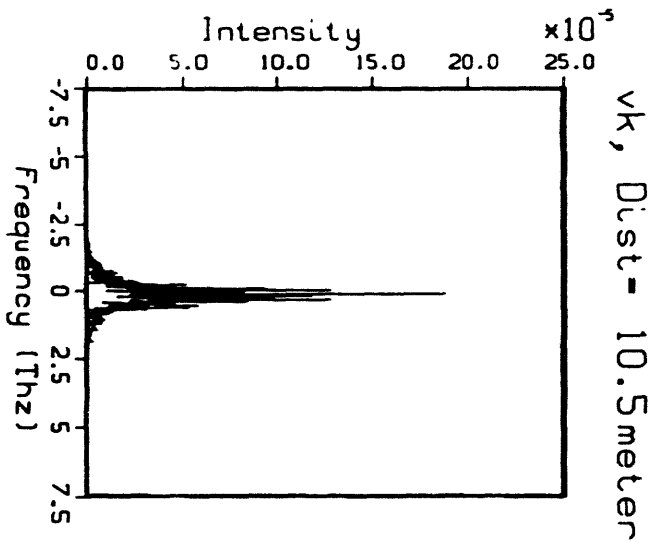
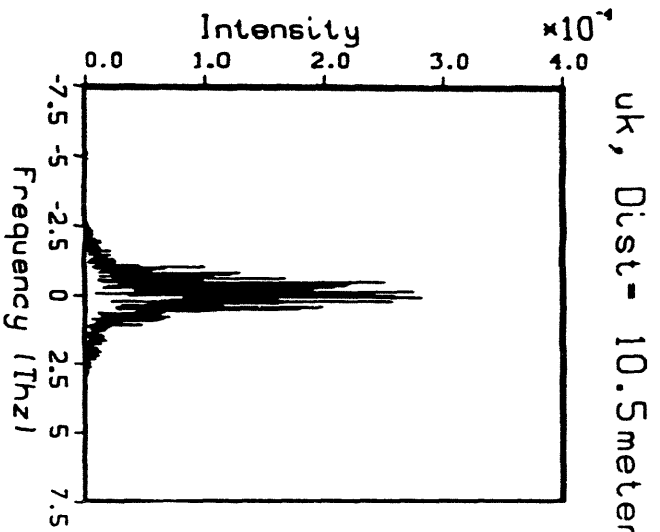
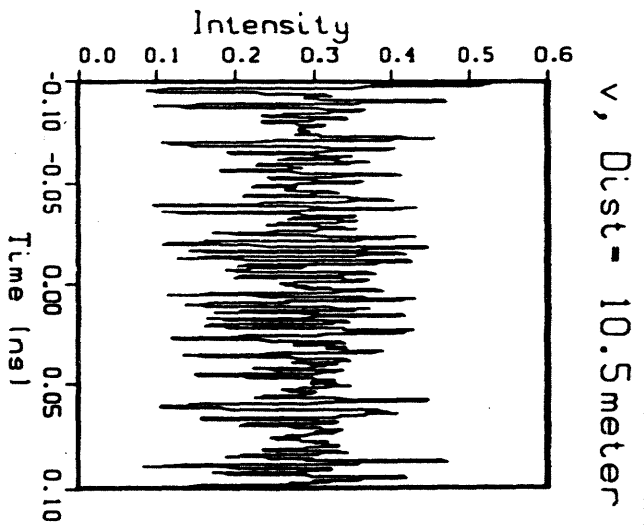
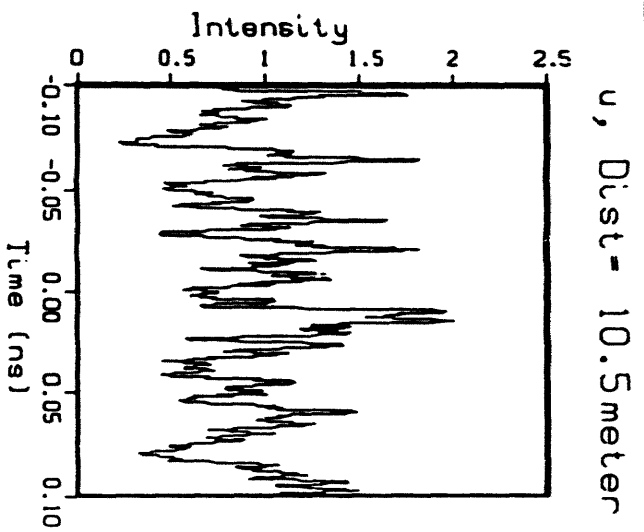


uk, Dist= 9.0meter

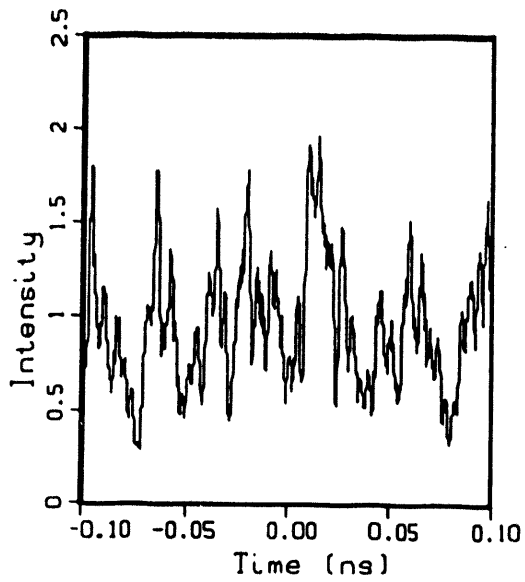


vk, Dist= 9.0meter

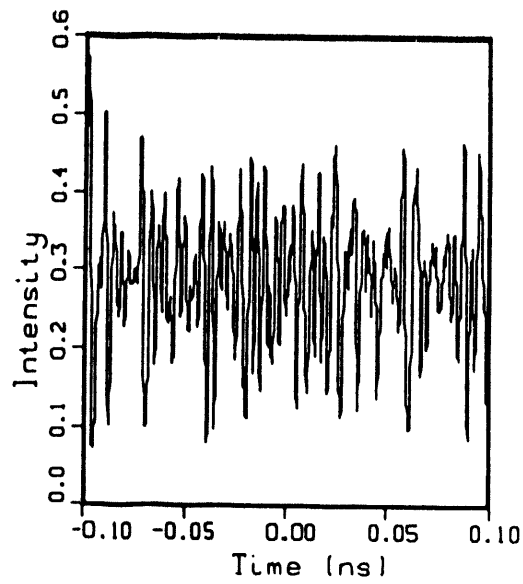




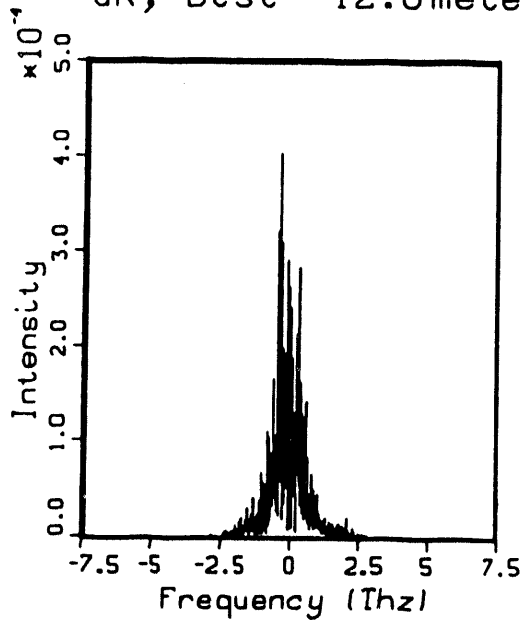
u, Dist= 12.0meter



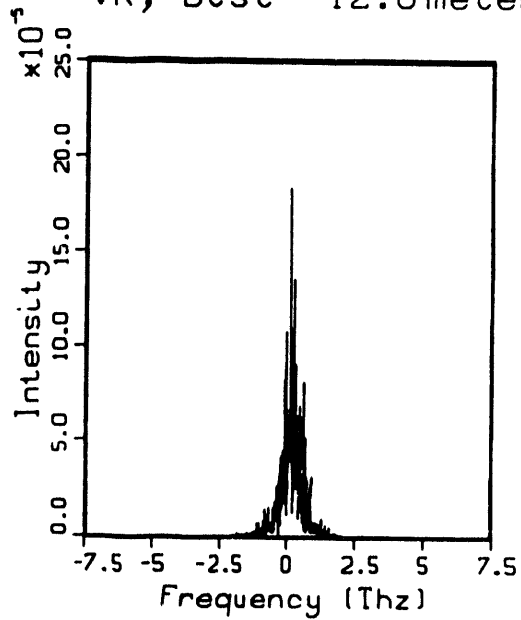
v, Dist= 12.0meter



uk, Dist= 12.0meter



vk, Dist= 12.0meter



Set #2

```

fper = 0.00050    length(m) =12.00000
xl(ns) = 0.10000
fm(m) = 1.50000
dn = 0.00006    B = 0.66667
dispersion(ps/nm/m) = -0.4000E-01
pump eng(uJ) = 5.0000
pump duration(ns) = 15.0000
pump spectral width(Ghz) =450.0000
signal eng(uJ) = 1.0000
signal duration(ns) = 10.0000
effective area(um**2) = 66.7200
amask = 0.0000
fmask = 1.0000

```

plotting parameters:

```

n=2048
xres= 2.000
xkres= 0.5000

```

u: the slow axis (broad band noise)

Dist (m)	I _{tsy} (W/um**2)	pk/avg	fcent (Ghz)	fwidth (Ghz)
0.00	4.9960	5.2167	0.0071	449.9909
1.50	4.9964	3.8672	-2.7067	1160.9778
3.00	4.9967	2.8585	-8.3079	1651.7415
4.50	4.9953	3.5700	-17.4739	1820.0343
6.00	4.9932	3.9009	-36.5357	1846.4571
7.50	4.9927	3.4896	-61.1025	1857.6529
9.00	4.9939	3.4720	-89.4246	1880.8240
10.50	4.9963	3.4654	-118.8392	1898.1362
12.00	4.9999	3.1382	-144.1741	1902.1172

v: the fast axis (signal)

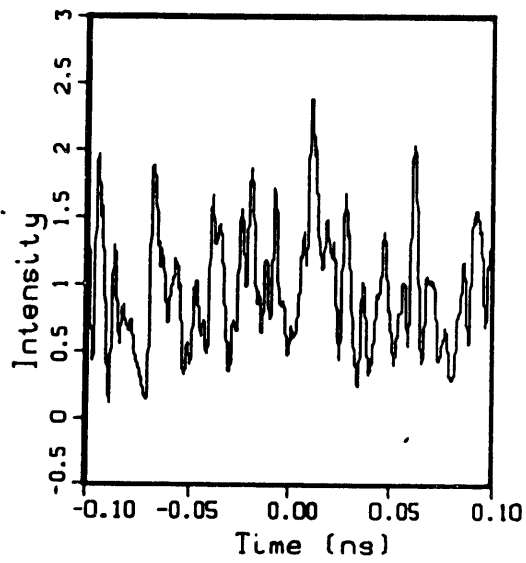
Dist (m)	I _{tsy} (W/um**2)	pk/avg	fcent (Ghz)	fwidth (Ghz)
0.00	1.4988	1.0000	0.0000	0.0000
1.50	1.4984	1.3390	2.4067	535.1697
3.00	1.4981	2.2494	14.1011	794.5739
4.50	1.4995	3.4393	25.6202	883.3265
6.00	1.5016	3.5447	40.8786	939.9976
7.50	1.5021	3.3432	61.5192	1038.4513
9.00	1.5009	3.7103	89.8415	1113.6283
10.50	1.4985	4.1601	113.1967	1220.8720
12.00	1.4949	4.1125	135.3833	1325.8064

Parameter values :

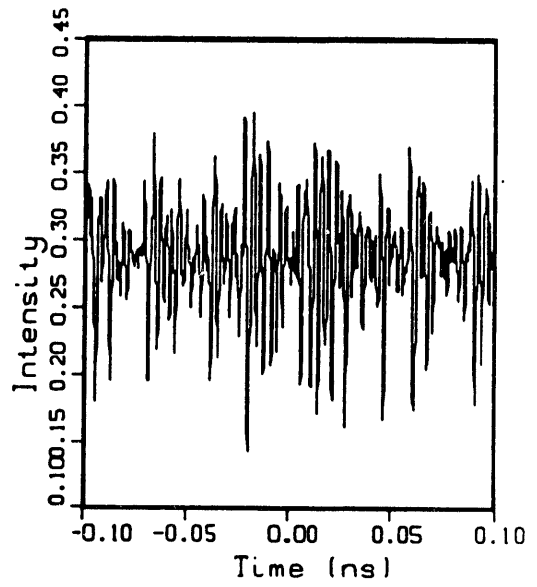
```
fper = 0.0005000
length(m) = 12.000
xl(ns) = 0.1000
fm(m) = 1.5000
dn = 0.0000600
B = 0.6667
dpsn(ps/nm/m) --0.0400
pmpeng(vj) = 5.0000
pmpdur(ns) = 15.000
pmpspwid(Ghz) = 450.00
sigeng(vj) = 1.0000
sigdur(ns) = 10.000
aeff(um**2) = 66.720
omask = 0.0000
fmask = 1.0000
n = 2048
xres(ps) = 2.0000
xkres(A) = 0.5000
```

!! Intensities, i.e., cabs(X)**2, are plotted !!

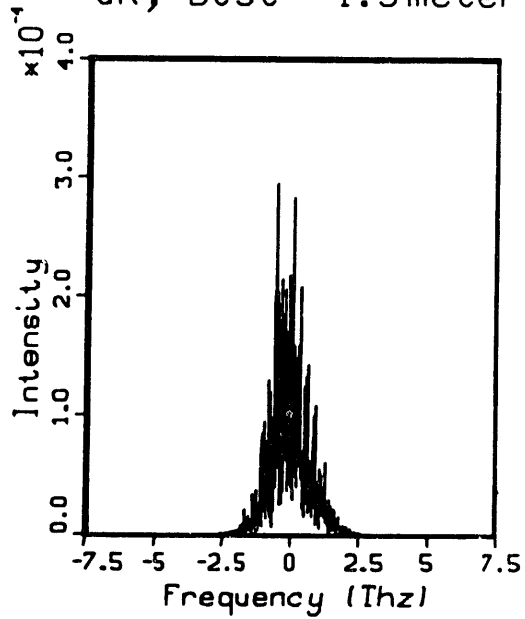
u, Dist= 4.5meter



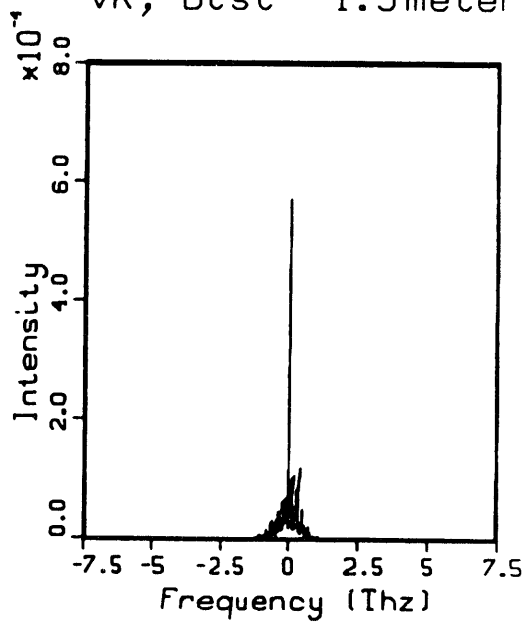
v, Dist= 4.5meter



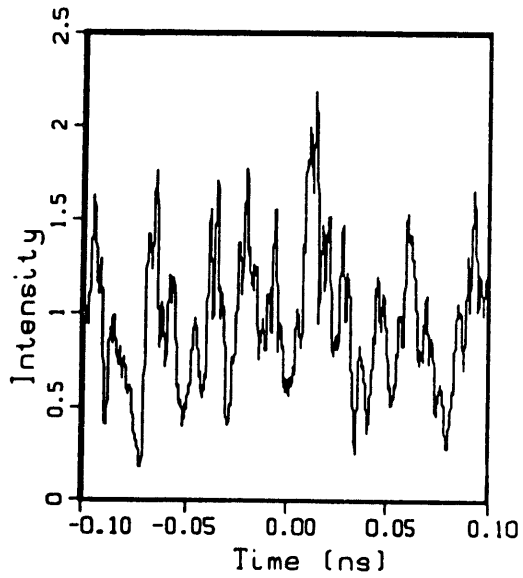
uk, Dist= 4.5meter



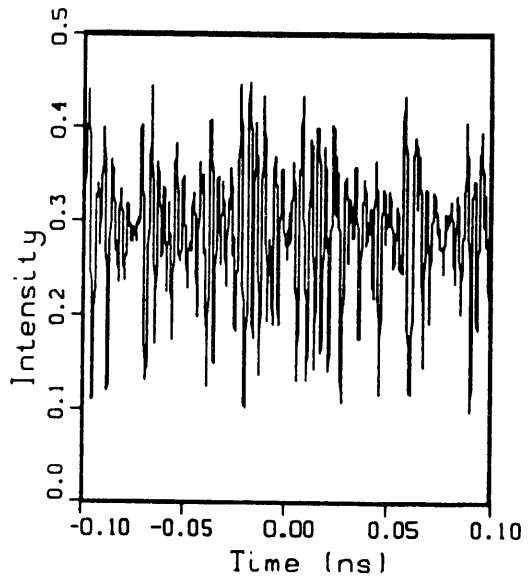
vk, Dist= 4.5meter



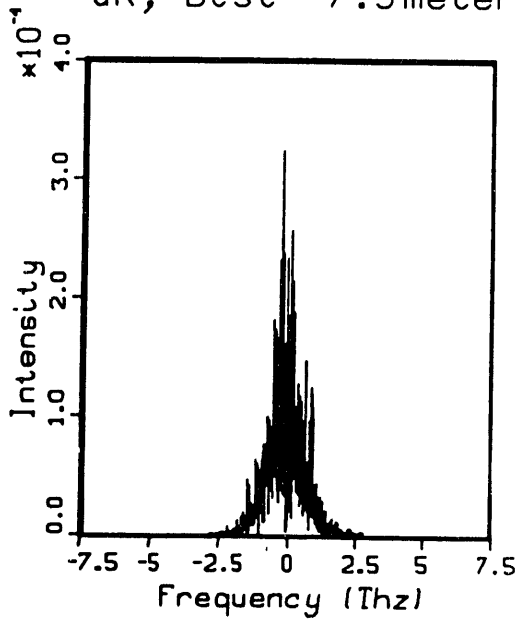
u, Dist= 7.5meter



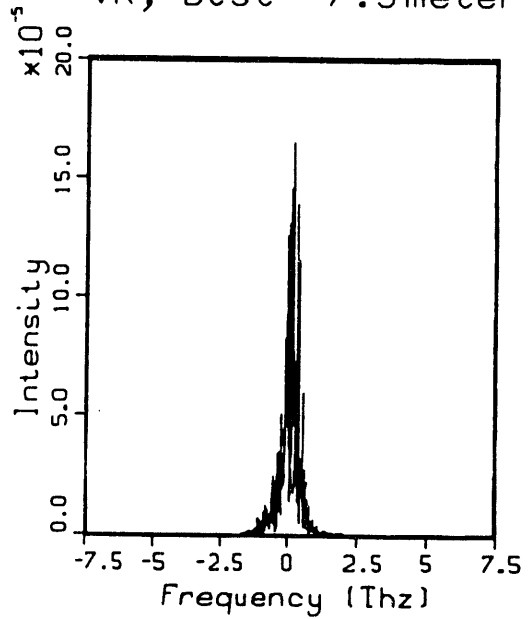
v, Dist= 7.5meter



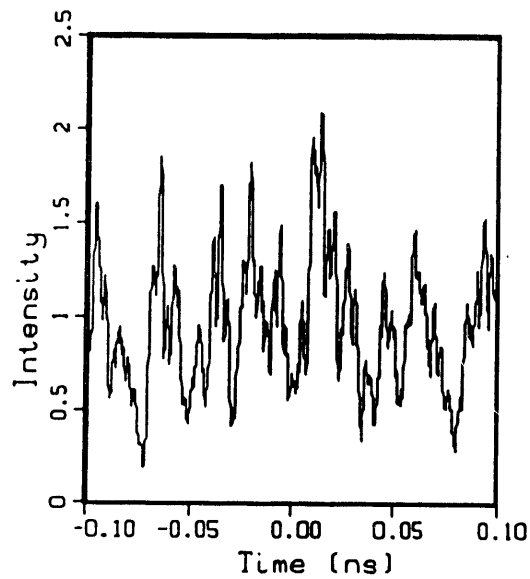
uk, Dist= 7.5meter



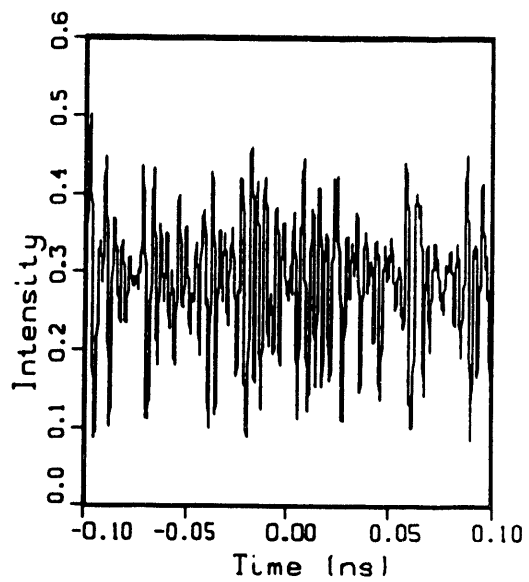
vk, Dist= 7.5meter



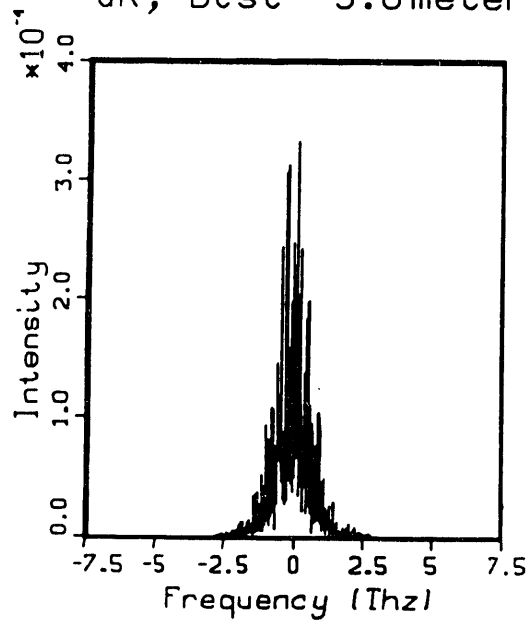
u, Dist= 9.0meter



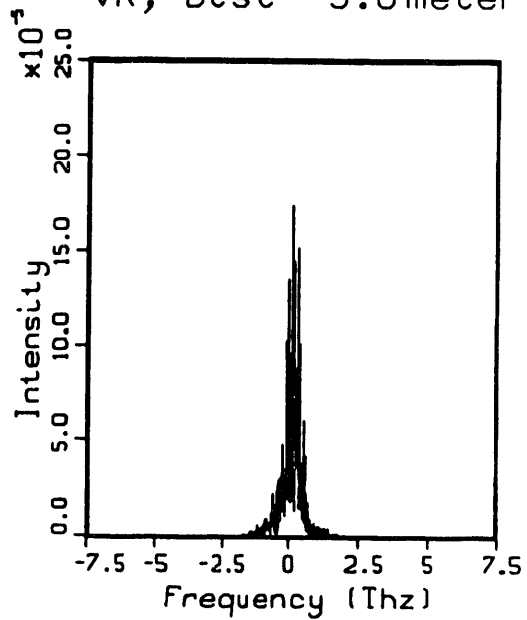
v, Dist= 9.0meter



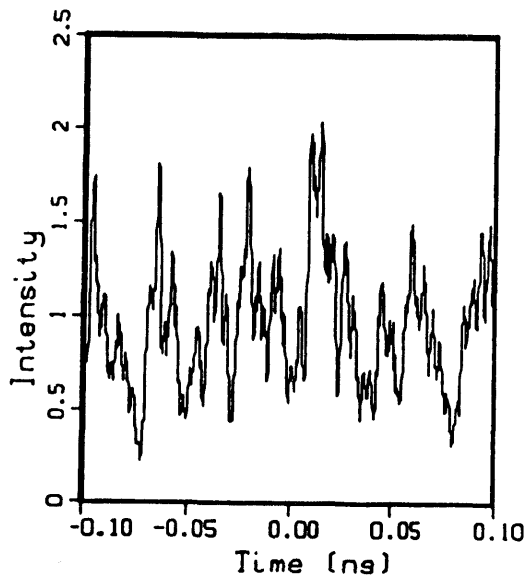
uk, Dist= 9.0meter



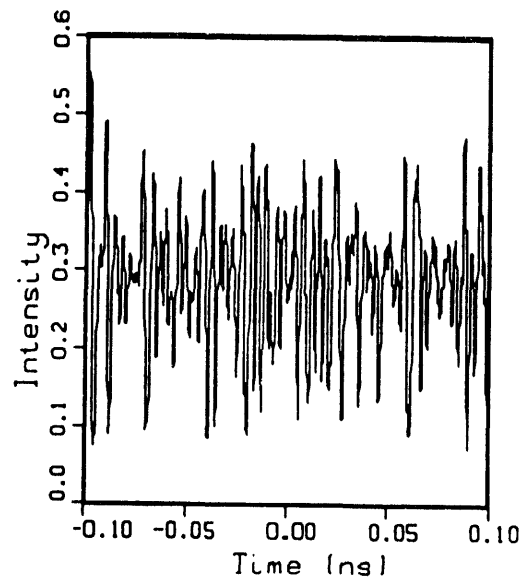
vk, Dist= 9.0meter



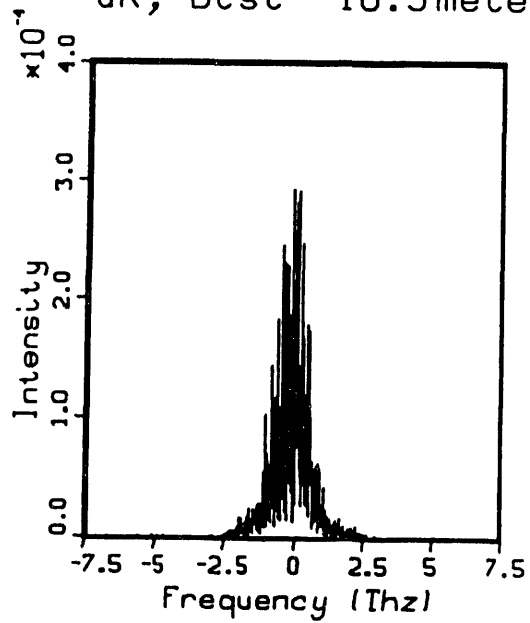
u, Dist= 10.5meter



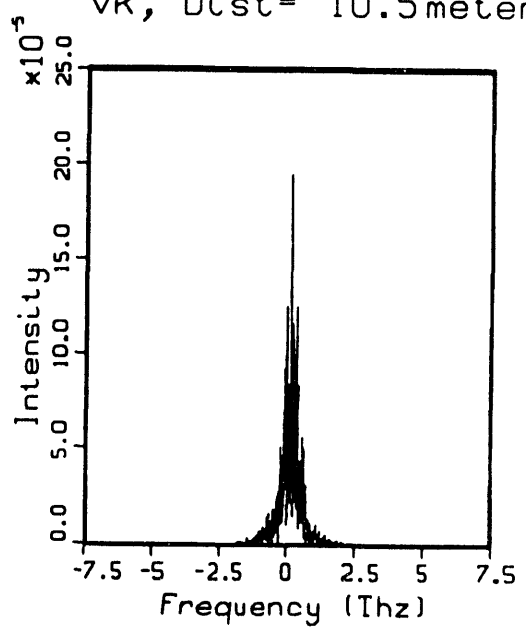
v, Dist= 10.5meter



uk, Dist= 10.5meter



vk, Dist= 10.5meter



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