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AMPLIFICATION OF A BI-PHASE SHIFT-KEY MODULATED SIGNAL BY A MM-WAVE FEL*

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Bi-phase shift keying (BPSK) is a modulation scheme used in communications and radar in which the phase of a transmitted rf signal is switched in a coded pattern between discrete values differing by π radians. The transmitted information rate (in communications) or resolution (in imaging radar) depends on the rate at which the transmitted signal can be modulated. Modulation rates of greater than 1 GHz are generally desired.

Although the instantaneous gain bandwidth of a mm-wave FEL amplifier can be much greater than 10 GHz, slippage may limit the BPSK modulation rate that can be amplified. Qualitative slippage arguments would limit the modulation rate to relatively low values; nevertheless, simulations with a time-dependent FEL code (GINGER) indicate that rates of 2 GHz or more are amplified without much loss in modulation integrity. In this paper we describe the effects of slippage in the simulations and discuss the limits of simple slippage arguments.

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1. Introduction

A mm-wave FEL amplifier has potential applications to radar imaging of objects at large distance (e.g., geosynchronous orbit); an FEL's advantages over more conventional mm-wave sources include large bandwidth and high average power at short wavelength. Resolution of an imaging radar along the line of sight ("range resolution") is determined largely by the bandwidth of the transmitted radar signal. A large bandwidth permits the outgoing signal to be rapidly modulated, which in turn permits the return signal to be compressed in time, concentrating the signal power into a short, high intensity spike from each reflector along the line of sight.

A specific pulse compression scheme that can be used with the pulse length (10s of ns to several μs) of an induction-accelerator-driven mm-wave FEL amplifier involves digitally coding the outgoing pulse by shifting its phase between 0 and π in a carefully chosen sequence. Range resolution is determined by the rate at which the phase shifting is done — two point reflectors along the line of sight can be resolved as long as they are separated by more than half the physical length of each bit in the coded sequence (see below). The phase shifting can be done at low power, before the final stage of amplification by the FEL. The question addressed by this paper is the upper limit to the rate at which the phase of the transmitted signal can be switched without being smoothed by slippage and other non-linearities in the FEL amplifier. We illustrate the effects of non-linearities with numerical simulations of a 94-GHz FEL amplifier.

2. BPSK coding

A simple example of bi-phase shift key (BPSK) modulation of a signal is shown in fig. 1: the signal has constant amplitude but is modulated in phase in a 7-bit Barker [1] code corresponding to a bit pattern of 1,1,1,-1,-1,1,-1 or a phase pattern of $0,0,0,\pi,\pi,0,\pi$. This particular pattern — as do the other Barker codes of N=2,3,4,5,7,11, and 13 bits — has the property that its autocorrelation (fig. 2) consists of a single sharp peak of amplitude N (7 in the example) with a maximum background ("sidelobe") level of 1. The autocorrelation compresses the pulse in time, with an initial amplitude of unity over N "chips" compressed to an amplitude of N in a single chip.

If a radar signal is transmitted with this kind of phase coding, the return signal can be correlated at the receiver with the transmitted code to produce a compressed signal with a sharp peak from each reflector along the radar line of sight. For an object comprising many reflectors in a complicated pattern, the compressed signal is the scaled profile of reflectivity vs range.

The length $c\delta$ (where δ is the time extent of each chip, $1/\delta$ is the chip rate, and c is the speed of light) of a single chip in the BPSK pattern limits the resolution of the radar image; two reflectors separated by less than $c\delta/2$ contribute to the same reflectivity peak in the range profile. (The factor of 1/2 arises because of the round-trip — to the object and back — made by the radar signal.) High resolution of the object being imaged therefore requires a high chip rate, which in turn implies a large signal bandwidth. Present state-of-the-art is a chip rate of 1-2 GHz, which could provide a range resolution of 7.5-15 cm. The FEL amplifier must be able to amplify this large bandwidth signal.

3. FEL amplifier bandwidth and slippage

At 35 GHz, ELF [2] demonstrated a detuning width of ±6% in magnetic field for a 3-m tapered wiggler with 35% extraction efficiency. This range in magnetic field corresponds to ±12% in frequency, or ±4.2 GHz. At higher frequency, an FEL amplifier is expected to have fractionally smaller but numerically larger bandwidth; fig. 3 shows the detuning curve obtained from numerical simulations of a 94-GHz tapered-wiggler amplifier. Parameters for the simulations are given in Table 1. The width of the detuning corresponding to a reduction of 1 dB from peak is seen from the figure to be 12.5 GHz. This bandwidth should be adequate to amplify a BPSK modulated signal with at least a 4-GHz chip rate.

From the simulation parameters of Table 1, it will be noticed that the slippage length $N_w\lambda$ (where N_w is 40, the number of periods in the wiggler, and λ is 0.32 cm, the signal wavelength) is 12.8 cm, or 425 ps. An individual slice of the electron beam interacts with a 425-ps length of signal pulse as the signal group velocity carries signal modulations over the more slowly moving electron beam. One might expect that abrupt phase transitions in the input signal would be smoothed by slippage into broad, ~400 ps long transitions at the output. Phase modulations would then have to be restricted to a chip length of much greater than 425 ps, or a chip rate of much less than 2.35 GHZ, in order not to be smoothed by slippage through the amplifier. Short pulse FELs are typically limited to less than 20% slippage; this would correspond to a maximum chip rate of 500 MHz. The chip-rate limit based on slippage is considerably more stringent than the limit based on a simple bandwidth argument. Fortunately, the slippage argument is of limited use.

4. Time-dependent FEL simulations of a BPSK signal

The importance of finite amplifier bandwidth and slippage can be explored by time-dependent numerical simulations of FEL amplification. GINGER is LLNL's time-dependent FEL simulation code; it is an extension of FRED [3] that permits many electron slices to evolve as the radiation field slips over them. In the simulations described here, it propagates a set of mm-wave signal slices and a set of electron beam slices with boundary conditions for both that are periodic in time at any axial position z. Because of the periodic boundary conditions, an appropriate input signal looks like fig. 4a or 4b, rather than the coded signal of fig. 1; the essential physics is fully examined by using the simple phase transitions of a two-chip periodic sequence.

Fig. 5 shows the signal phase vs time after amplification of a 94-GHz carrier modulated at 1-, 2-, 3-, and 4-GHz chip rates. The phase transitions are amplified fairly cleanly up to 3 GHz, well beyond the limit suggested by the slippage argument, but are significantly smoothed at 4 GHz.

Fig. 6 shows the signal power accompanying the phase plots shown in fig. 5, as a function of time. As one would expect, the finite bandwidth of the FEL amplifier has introduced amplitude modulations into the initially unmodulated (in amplitude) signal.

It is immediately apparent from the phase vs time plots of fig. 5 that the phase transitions from 0 to π in the input (fig. 4) have become transitions from 0 to $-\pi$; that is, the large positive $\partial\phi/\partial t$ between chips has become negative. This conversion does not affect the coding or the pulse compression, because the +1/-1 nature of the chips is preserved. The phase-slope conversion occurs early in the simulations, before saturation of exponential gain. Transitions with $\partial\phi/\partial t > 0$ steepen and reverse, while transitions with $\partial\phi/\partial t < 0$ spread and flatten. The steepening or flattening occur in the simulations because of a combination of differing gain in the transition regions, and sensitivity of phase to signal amplitude:

$$\frac{\partial\phi}{\partial t} + v_g \frac{\partial\phi}{\partial z} \propto \frac{\langle\cos\psi\rangle}{E_s} \qquad (1)$$

where v_g is the group velocity of the signal, ψ is the phase of an electron in the ponderomotive potential well, E_s is the signal electric field, and the angle brackets represent an average over the electron distribution. The quantity $\langle\cos\psi\rangle$ therefore quantifies the bunching, and a smaller E_s at a fixed bunching increases the phase advance.

5. Effects of reduced slippage

Changing the dimensions of the waveguide can change the signal group velocity, and hence affect slippage [4]. Slippage of the TE_{01} mode vanishes if the condition [5]

$$b^2 = \frac{\lambda \lambda_w}{4} \qquad (2)$$

is met, where b is the full width of the waveguide in the dimension out of the plane of the wiggler motion and λ_w is the wiggler wavelength. For the parameters of the FEL described in Table 1, this condition is met for b = 0.9 cm. Such a waveguide would be narrower than the electron beam and therefore impossible.

Reduced, but non-zero, slippage can be achieved with a slightly bigger waveguide. Slippage is reduced by ½ for b = 1.22 cm, a size greater than the electron beam size (but in practice, still too small to handle the kind of power required for a radar application). Fig. 7 shows phase vs time for an amplified signal with a 4-GHz chip rate, identical to the lower right plot of fig. 6 except for a reduced b = 1.22 cm (and a reduced wiggler magnetic field to compensate for the changed signal *phase* velocity). Surprisingly, the output phase is smoothed in a very nearly identical fashion. The explanation appears from examining the phase plots at 2, 3, and 4 m. With full slippage (fig. 5d) the phase profile at 2 m is very nearly identical to the profile at 4 m, indicating that the phase smoothing has saturated by ~ 2 m. With half the slippage (fig. 7), the smoothing does not saturate until ~4 m, and the phase profile at 2 m shows approximately half the smoothing (i.e., considerably sharper transitions) of the case with full slippage. A mechanism that saturates the smoothing effect of slippage is obviously not included in the usual simple slippage arguments (Sec. 3).

6. Summary and conclusions

Although a mm-wave FEL can be a very broad-band amplifier, slippage limits the BPSK modulation rate that can be amplified. TIme-dependent simulations indicate that the achievable modulation rate is considerably higher than simple slippage arguments would imply. In the high-gain regime, a slippage length based on a gain length, rather than on the full wiggler length, appears to be more appropriate. In addition, smoothing of the phase transitions between BPSK chips saturates well before the phase modulation has been completely washed out.

Acknowledgements

We are happy to thank Frank Chambers and Fred Coffield for useful discussions.

Table 1
FEL simulation parameters

Electron beam	
Energy	4 MeV
Current	2 kA
Emittance (normalized, 90%)	0.002 π m-rad
Radius	0.48 cm
Wiggler	
Period	10 cm
Length	4 m
Field strength (z = 0)	2.78 kG
(z = 4 m)	1.03 kG
Taper	3%/period from 1.9 m
Waveguide	
Size	3.5 X 4 cm
mm-wave signal	
Frequency	94 GHz
Interaction mode	TE_{01}
Input power	1 kW
Output power	2.35 GW
Extraction efficiency	29.4%

Figure captions

Fig. 1. Amplitude and phase of a 7-bit bi-phase shift-key modulated signal. Information is coded in the pattern of the carrier phase in the seven bits.

Fig. 2. Autocorrelation function of the BPSK pattern of fig. 1. The usefulness of this coding arises because of the sharp peak at zero displacement.

Fig. 3. Detuning curve from numerical simulations of the FEL amplifier whose parameters are given in Table 1. The bandwidth of the amplifier is 12.5 GHz between frequencies for which gain is reduced 1 dB from peak, and 17.5 GHz between the 3 dB points.

Fig. 4. Phase modulations introduced at the entrance to the wiggler in the time-dependent FEL simulations. The simulation code GINGER assumes the pattern within the time window to be periodic in t at any given z.

Fig. 5. Phase vs time for the amplified signal at four different chip rates: (a) 1 GHz, (b) 2 GHz, (c) 3 GHz, and (d) 4 GHz. Up to a 3-Ghz chip rate, the phase transitions are amplified without serious degradation by slippage.

Fig. 6. Output power vs time for the amplified signal with the four chip rates of fig. 5.

Fig. 7. Phase vs time for the amplified signal at 4-GHz chip rate (analogous to the plot of fig. 5d) in a smaller waveguide, b = 1.22 cm. The smaller waveguide reduces the group velocity of the 94-GHz carrier, and so reduces the slippage, but does not significantly reduce the smoothing by slippage.

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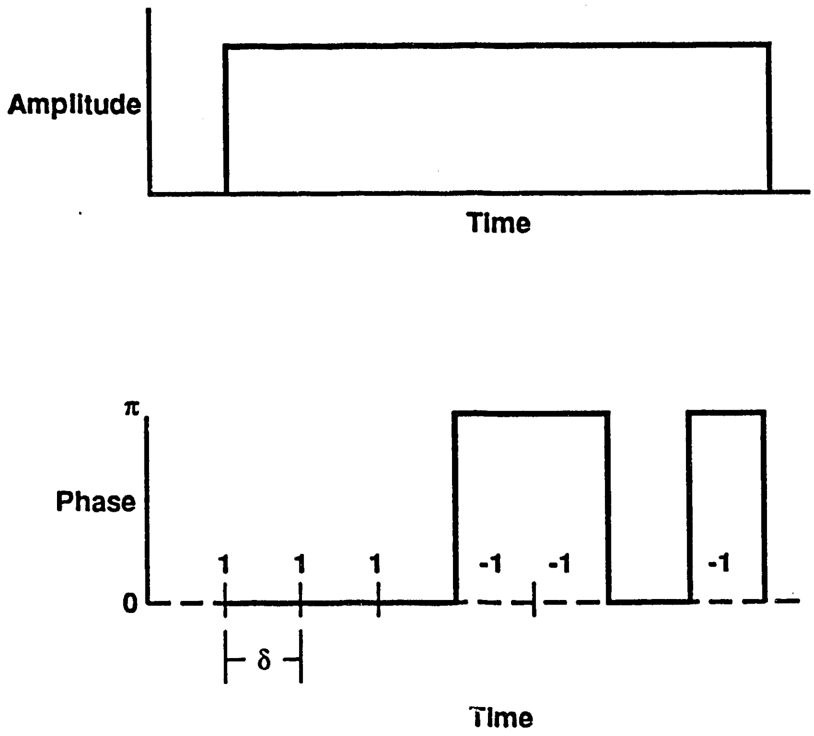

Fig. 1

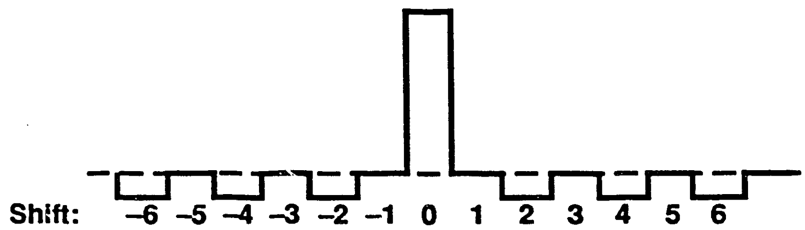

Fig. 2

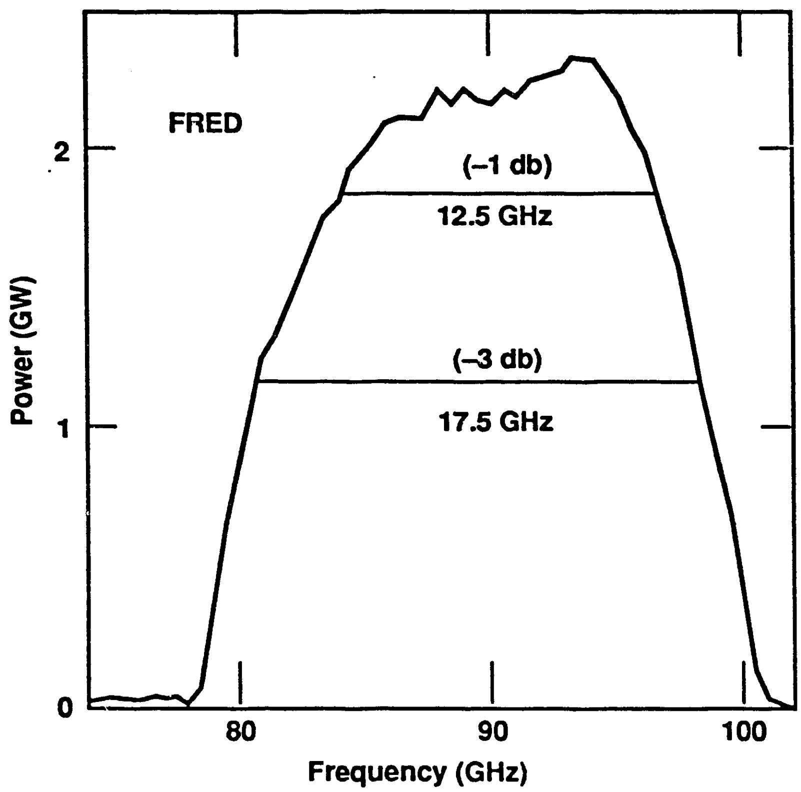
FRED
2
(–1 db)
12.5 GHz
Power (GW)
(–3 db)
17.5 GHz
1
0
80
90
100
Frequency (GHz)

Fig. 3

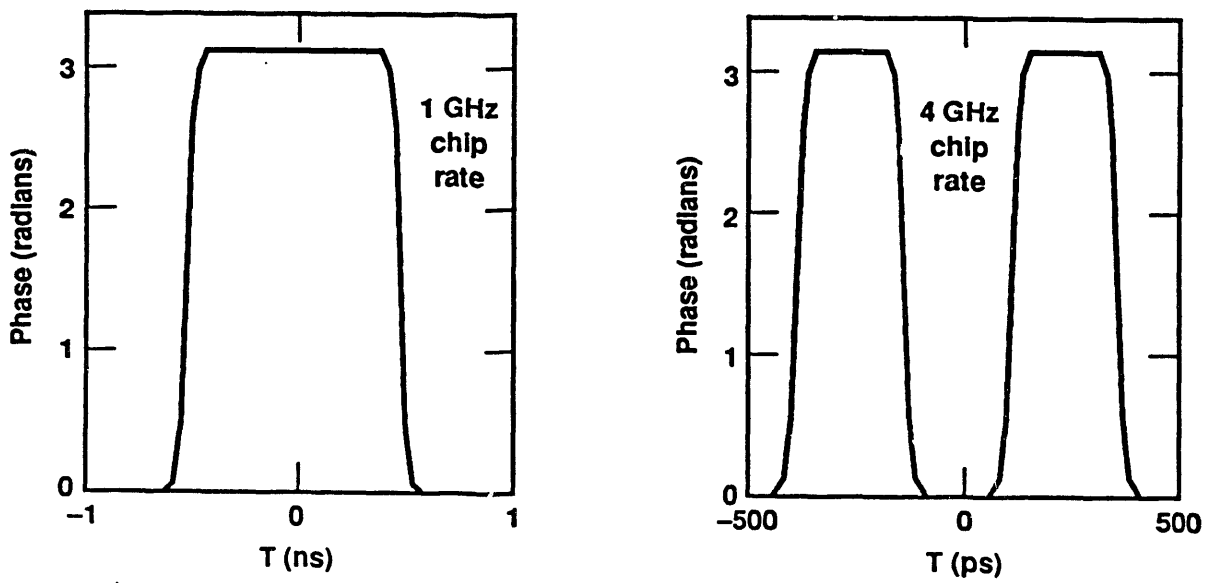

Fig. 4

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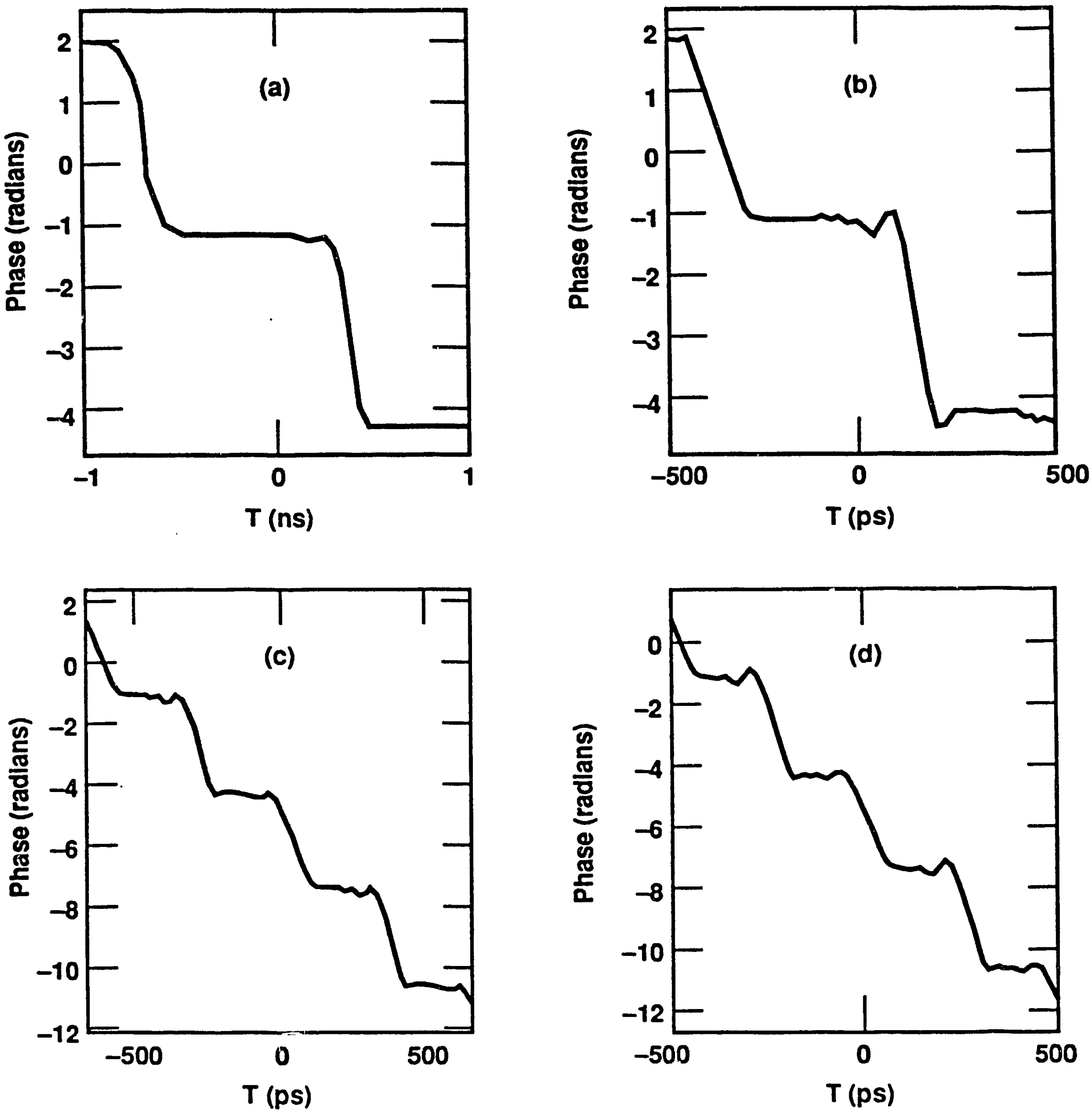

Fig. 5

CLC-S10-U-19033-1837

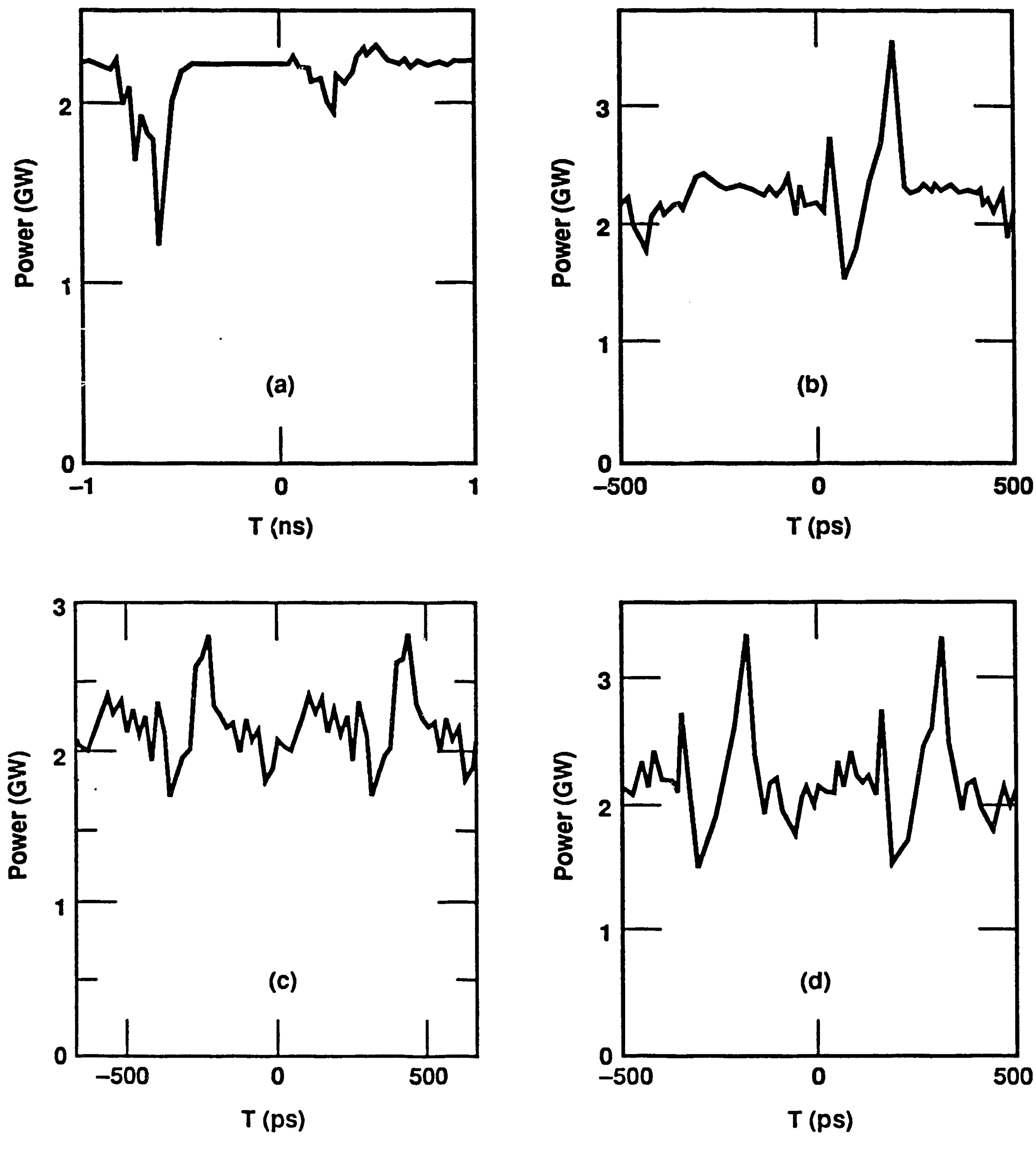

Fig. 6

CLC-S10-U-19033-1838

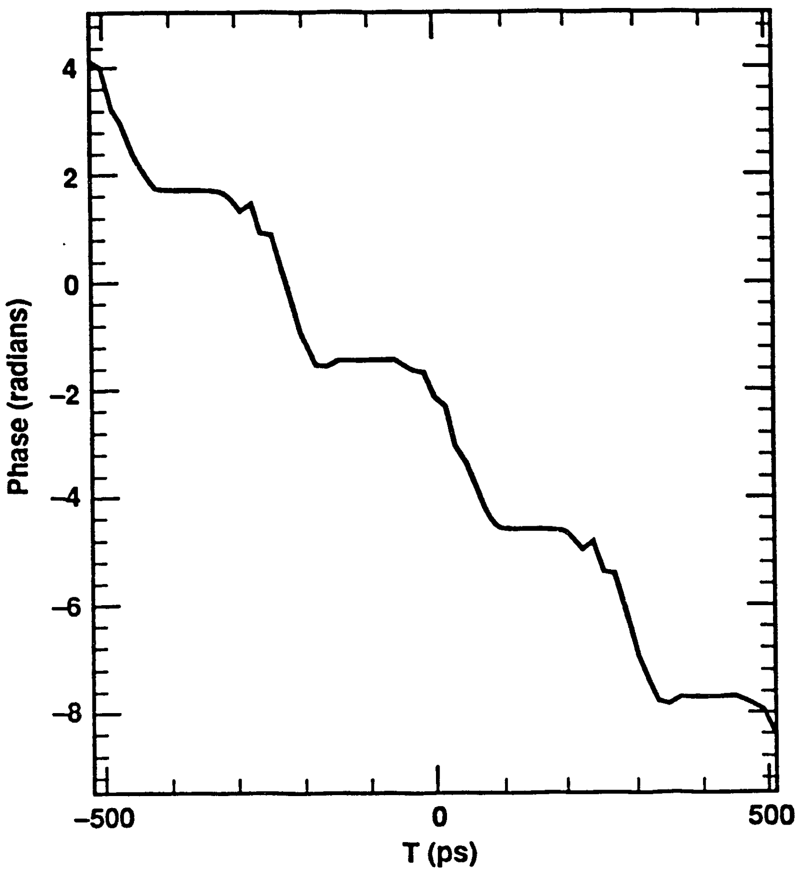

Fig. 7

CLC-S10-U-19033-Fig 7

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