SIMPLE MAGNETOSTATIC DELAY LINES IN MICROWAVE PULSE COMPRESSION LOOPS

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ABSTRACT

A magnetostatic surface wave (MSSW) delay line has been evaluated theoretically and experimentally as a microwave pulse compression filter in an active generation compression loop. The MSSW delay line had a 570 MHz bandwidth (based on the half pulse width), centered at 2.9 GHz, with 53 nsec of delay dispersion, for a time-bandwidth product of 30. Measured time-sidelobes were 15.8dB below the main pulse with a theoretically predicted peak-to-sidelobe ratio of 19.6dB. Effects of Doppler shifts, delay line characteristics, spectral weighting, and FM predistortion were included.

INTRODUCTION

Pulse compression systems utilizing surface acoustic wave (SAW) devices have been under intensive investigation for the past 10 years. These studies have concentrated primarily on linear chirps and the achievement of low time-sidelobes by appropriate amplitude weighting. Both active and passive generation have been utilized in the compression loops, and time-sidelobes of greater than 40dB down and time-bandwidth products >1000 have been obtained. In general, SAW devices achieve large processing gains by large time delays (1-100 µsec) with bandwidths from 50-500 MHz.[1] A new technology based on "slow" magnetostatic wave (MSW) propagation in a magnetically biased epitaxial yttrium iron garnet (YIG) is emerging as a complementary technology to SAW at microwave frequencies (1-20 GHz). Spin coupling in the magnetostatic modes results in electromagnetic wave propagation at group velocities two orders of magnitude below the speed of light.[2] This slow wave structure makes the investigation of MSW devices in pulse compression loops logical.

MSW devices achieve comparable processing gains through large bandwidths (nominally 0.5-1.0 GHz) accompanied by typical group delays of up to 1000 nsec/cm, depending on the bias field and film thickness used. The 1-20 GHz center frequency range and 2 GHz bandwidth capability of this technology makes processing possible directly at radar carrier frequencies. Center frequencies are electronically tunable by adjusting the magnetic bias field strength (375 Oe at 3 GHz with MSSW).[2]

This theoretical and experimental investigation focuses on use of the intrinsic MSW dispersion in a pulse compression loop formed from an active chirp generator and a simple magnetostatic surface wave (MSSW) delay line.

Experimental objectives were to establish performance limits for the simplest possible system. Although performance gains can be realized with added complexity -- such as metalized arrays for spectral weighting and delay linearization-- a simple delay line could be adequate for numerous less demanding applications at considerable cost and manufacturing savings.

THEORY

The delay line was modeled theoretically with typical experimental values for parameters; 30 µm YIG thickness, 0.51 mm thick gadalinium gallium garnet substrate, 1.5 cm long and 3.0 mm wide. In the experiment a pair of single-bar narrow shorted microstrip transducers, 50 µm wide and 2.5 mm long were deposited photolithographically in 2.0 µm aluminum directly on the YIG surface, which was spaced from ground by the GGG substrate. Earlier work by Wu[3] provided the amplitude response (figure 3a) and group delay (figure 3b) used in the theoretical predictions. Wu modeled the transducers (mainly responsible for the roll off) as low-loss microstrip transmission lines, with MSW excitation corresponding to a radiation loss. The theoretical group delay was calculated using a four layer dispersion relation after Collins, Owens and Smith.[2]

These two characteristics completely define the delay line transfer function,

$$A(\omega) = |A(\omega)|\, e^{j\ell\,\Phi(\omega)}$$

For best signal-to-noise in the recompressed pulse, the VCO must be swept so that the transform of its chirp,

$$S(\omega) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{+\infty} a(\tau) \cos[\omega_o \tau + \Theta(\tau)]\, e^{j\omega\tau}\, d\tau,$$

$a(t)$ = chirp envelope

$\Theta(t)$ = sweep function

conjugately matches the delay line characteristic,

$$S(\omega) = A^*(\omega)$$

Since most high power radar transmitters operate class-C, $a(t)$ was considered constant in amplitude for the pulse duration allowing only phase matching in the transforms. A stationary phase approximation,

$$\Theta(t) = \omega_o t + \ell \int \left|\frac{d\Phi(w)}{d\omega}\right|^{-1} dt,$$

valid for large time-bandwidth products, was used to facilitate calculation of the required conjugate sweep.[4]

Separate programs were written for the digital computer to model the swept VCO and delay line. The results from the first program verified the stationary phase approximation by using $a(t)$ and $\Theta(t)$ to calculate arg $[S(\omega)]$ and $|S(\omega)|$. This transform of the chirp, $S(\omega)$, then served as the input for the second program which modeled the delay line compression using

$$r(t) = \frac{1}{2\sqrt{2\pi}} \int_{m(\omega_o - \pi BW)}^{\omega_o + \pi BW} S\left(\frac{\omega}{m} - \omega_o\right) F(\omega)\, d\omega$$

where

$$F(\omega) = A(\omega - \omega_o) \cos\left[\omega t + \ell\left[\Phi_T(\omega) - \Phi_R\left(\frac{\omega}{m}\right)\right]\right]$$

This second program predicted a 19.6dB upper bound on the peak-to-sidelobe ratio for the simple MSSW delay line pulse compressor. Of particular concern was the effect of Doppler shifts in conjunction with the nonlinear delay on this sidelobe level. In the compression integral,

$$m = 1 + 2v_{object}/c$$

models the Doppler effect. Computer runs with target relative velocities up to 1800 MPH with an assumed 95 GHz radar carrier frequency showed less then 0.10dB of peak-to-sidelobe degradation.

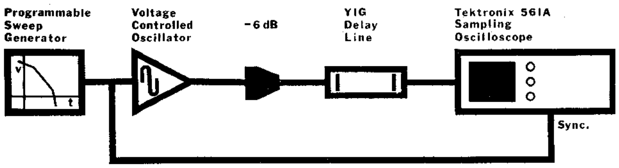

FIGURE 1: Pulse compression loop using a simple MSSW delay line.

EXPERIMENT

As shown in figure 1, the experimental setup consists of four basic blocks. In the transmitter portion of the compression loop, both active and passive generation were considered. Impulsing either forward or reverse volume wave delay lines looks promising for passive generation and recompression (as corresponding delay time-frequency curves have opposite slopes), and active generation using a programmable sweep generator offers the possibility of sidelobe reduction by FM-predistortion after tuning out nonlinearities in the VCO and matching the receiver delay. Active generation was use for this work.

A programmable voltage sweeper which approximated a continuous sweep with seven linear segments whose slopes and cut-on points could be independently set was designed. The linear segments were generated by bipolar constant current sources charging a common capacitor. Each current source was configured like a programmable unijunction transistor to provide a programmable turn-on point. A Schmitt Trigger was used as a feedback element to reset the capacitor and give self sustained sweep oscillation with a 70 KHz repetition rate. Since the nominal sweep time was 100 nsec, this repetition rate allowed ample idling time for transients from the previous pulse to subside. The 23V sweep drove the VC O output well beyond both sides of the delay line passband, eliminating need for pin-diode pulse truncation.

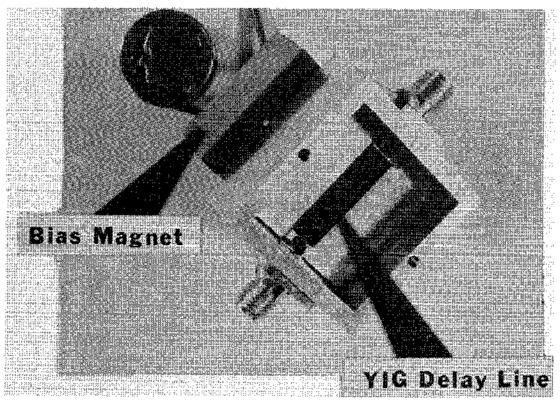

FIGURE 2: The experimental device mounted in its shielded case, with bias magnet.

A Watkins-Johnson WJ-V302 VCO covering a 2 to 4 GHz frequency range with a minimum power output of 13 mW, and a 20 MHz FM bandwidth was used. A 6dB divider was inserted before the delay line as a safeguard against saturation. Nonlinearities in the voltage-frequency curve of the VCO were lumped with the nonlinearity of the delay line group delay to generate the required time-voltage characteristic. Dynamic measurement of the chirp envelope revealed ripple >15dB down, verifying the validity of the constant envelope assumption. Thus, the required time-voltage relation for the sweep generator could be found graphically from the measured delay line characteristic and the measured VCO voltage-frequency curve.

The MSSW delay line described previously was biased transverse to the propagation direction in the plane of the film by a small horseshoe magnet mounted outside of the shielding case, with the pole faces straddling the line.

A Hewlett Packard 8410B network analyzer was used to measure the delay line spectral amplitude, $|A(\omega)|$ (figure 3a), and group delay (figure 3b),

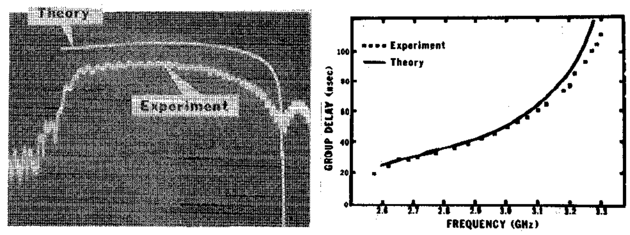

FIGURE 3: (a) Measured and theoretical delay line spectral amplitude (Horiz: 2.4 - 3.4 GHz, Vert: 10dB/div).

(b) Measured and theoretical group delay characteristics.

$$\tau_G(\omega) = \frac{\ell d\Phi(\omega)}{\omega}$$

via the slope of the phase characteristic. As seen in the figure, the amplitude response was centered at 2.9 GHz with a 16dB minimum insertion loss. Reciprocating the first zero crossing of the compressed pulse resulted in a 570 MHz effective bandwidth, spanning 53 nsec of delay dispersion, for a time-bandwidth product of 30. Need for down conversion of the recompressed pulse was eliminated by using a Tektronix 564/2S2/S4 sampling oscilloscope to view the recompressed pulse directly out of the delay line. Synchronism was obtained by triggering from the sweep generator. An oscilloscope trace of the recompressed pulse along with a comparison to the theoretical prediction is shown in (figure 4).

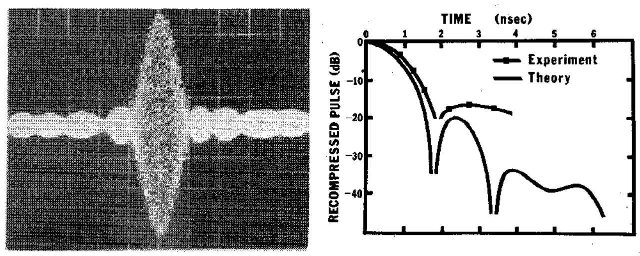

FIGURE 4: (a) Sampling scope trace of recompressed pulse emerging from delay line (Horiz: 2nsec div., Vert: 1.27 volts/div.).

(b) Comparison to theory.

The sweep generator was initially programmed for the theoretical sweep and then fine tuned to maximize the peak-to-sidelobe ratio to 15.8dB. In good agreement with theory, the first zero crossing occured at 1.85nsec.

Doppler shifts were simulated by varying the DC level at the VCO sweep input. Voltage offset was translated into a frequency shift by using the slope of the VCO characteristic, f(v), at 2.9 GHz. Both positive and negative shifts were used resulting in less than 0.16dB peak-to-sidelobe degradation for simulated target velocities up to 1800 MPH, as predicted by theory (figure 5).

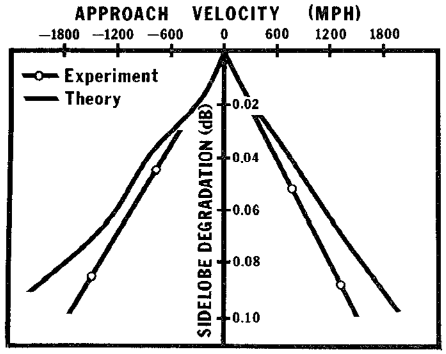

FIGURE 5: Effect of nonlinear YIG group delay on peak-to-sidelobe level in a Doppler environment.

RESULTS AND CONCLUSIONS

Overall, model predictions were in good agreement with experimental results. The approximation of the sweep function in the actual compression loop is the most likely source of differences between theoretical predictions and experimentally observed pulse 3dB-width and peak-to-sidelobe ratio. Since the zero crossings are mainly fixed by the amplitude response, reduction in the height of the main lobe due to the sweep approximation would cause the pulse to be wider at the 3dB points. In addition, if the sidelobes were not identically effected by the approximation, a degradation in the peak-to-sidelobe ratio could result. Better delay matching could be attained by going to a longer delay (thinner film) recompression line, since this would result in a larger time-bandwidth product.

A particularly important result of this work was the peak-to-sidelobe immunity to Doppler shifts reflected in both theory and experiment (<0.16dB degradation for $v \le 1800$ MPH and $f_c = 95$ GHz). The effect of the nonlinear group delay on Doppler sensitivity had been a major concern for investigation in this work since radars intrinsically operate in a Doppler environment.

Further improvement in the peak-to-sidelobe ratio is possible by Hamming weighting the spectrum amplitude. With large time-bandwidth products, the stationary phase approximation,

$$|S(\omega)|^2 = \frac{d\left[\left(\omega_o + \frac{d\theta(t)}{dt}\right)^{-1}\right]}{d\omega}$$

provides an easy way to achieve spectral weighting by predistorting the sweep function, $\theta(t)$.[5] Such predistortion is accompanied by unavoidable delay missmatch, so it is imperative that it be used in moderation. The amount of predistortion required could be minimized if the transducers were designed to give a passband already approximating the limiting weighting. Loop transducers are being considered for this use, since the associated interbar phase interaction significantly increases the roll-off at both delay line passband edges producing a resemblance to the Hamming weighting. Theory predicts a 28.75dB peak-to-sidelobe ratio in a recompressed pulse with the loop transducer spectral weighting and appropriate nonlinear frequency sweep.

SUMMARY

THE COMPRESSION FILTER--

Magnetostatic Surface Wave, launched from a pair of single-aluminum-bar narrow shorted microstrip transducers.

Effective Bandwidth: 570 MHz, based on half the recompressed pulse width.

Delay Dispersion: 53 nsec over the effective bandwidth.

Time-Bandwidth Product: 30.

Completely Self-Contained, with its own 375 Oe bias magnet.

THE RECOMPRESSED PULSE--

Peak-to-Sidelobe Ratio: 19.6 dB -- theoretical
15.8 dB -- experimental

Half Pulse Width: 1.78 nsec-- theoretical
1.85 nsec-- experimental

Doppler Sidelobe Sensitivity:
0.10 dB degradation--theoretical
0.16 dB degradation-- measured

FUTURE--

Experimental goals are to increase the peak-to-sidelobe ratio to a usable level (25 dB) using

(I) fm--predistortion

(II) Loop Transducer Amplitude Weighting

to effect an approximate Hamming spectral weighting.

ACKNOWLEDGMENTS

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