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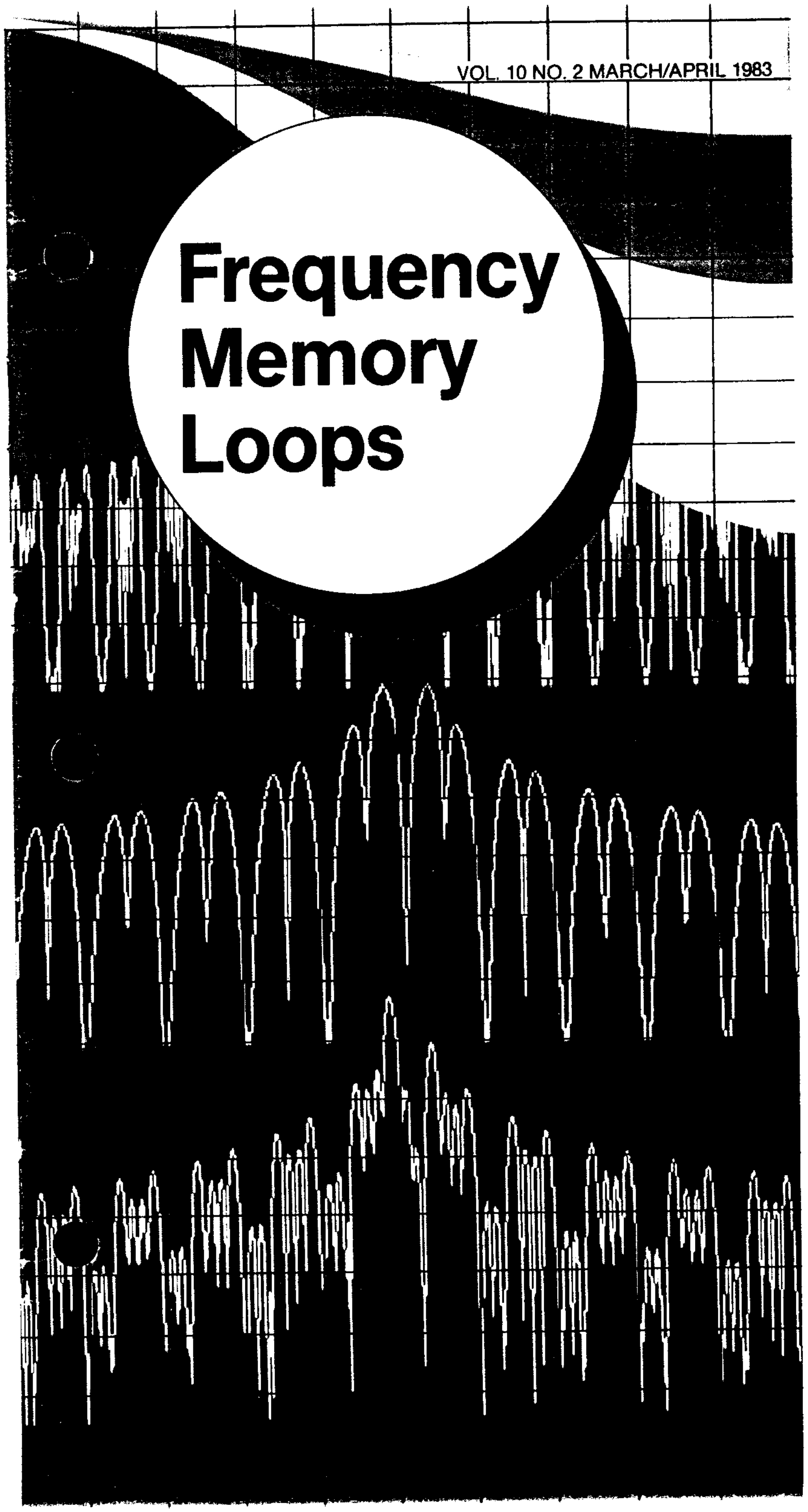
Frequency Memory Loops



The frequency memory loop (FML) is an electronic countermeasure designed to deny range-to-target information to a threat radar. A tracking radar determines target distance by measuring the time the radar pulse takes to travel to the target and back. By "memorizing" the radar's incident pulse frequency and retransmitting it at a carefully controlled time, the FML is able to deceive the threat radar. The process employed is called Range Gate Pull-Off (RGPO).[1]

Figure 1 shows the RGPO process schematically. The sequence of events is as follows:

1. At the start of one RGPO cycle, the incident radar pulse is returned with minimum delay. This delay must be small compared to the radar pulse width in order for the returned signal to coincide in range with the real target echo. A typical tracking radar pulse width is 0.5 to 2 μs, while an FML has a minimum delay of less than 10 ns. The power of the returned pulse must exceed the target echo power by about 10 dB to capture the attention of the threat radar in the presence of the real signal.
2. Once the FML has captured the threat, the returned pulse is delayed slightly more for each received pulse before being re-radiated, thus pulling off the range gate. Typical pull-off rates are about one μs per second.

The maximum range gate pull-off is determined by the time for which an FML is able to store information. After the range gate has been pulled to this maximum, the ECM system quickly snaps back to the minimum delay. The threat radar is unable to follow this quick change, and it sees the target vanish from its range gate. The radar must go into its search mode to reacquire the target, and the whole process is repeated (preferably in some non-predictable sequence) by the ECM system. The effect of the ECM is that the threat radar will be operating with true information for only a small fraction of the time.

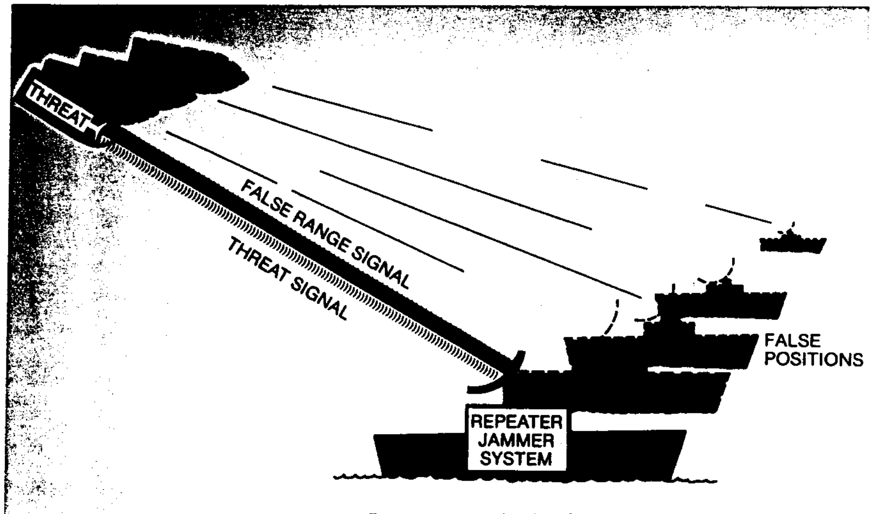


Figure 1. Range gate pull-off ECM.

FML Operation

A block diagram of an FML is shown in Figure 2. Its operation is as follows:

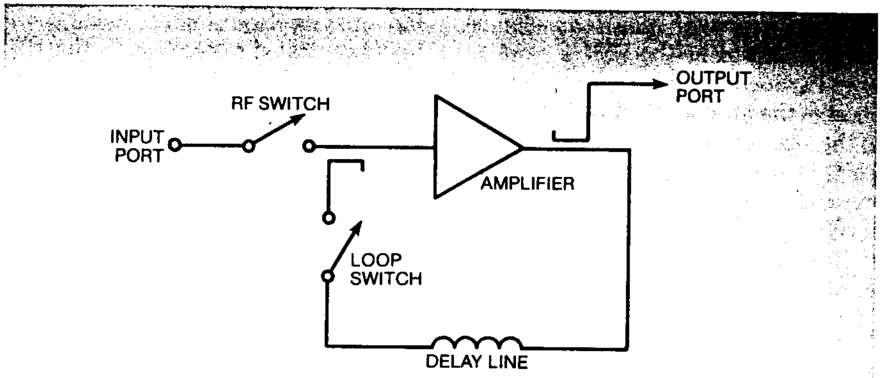


Figure 2. Frequency memory loop.

1. The FML is in a "standby" state when the RF switch is closed and the loop switch is open. An RF pulse enters through the input port. The leading edge of the pulse propagates through the amplifier and the delay line to the position of the loop switch. At this point, the entire loop is "filled" with RF (assuming a sufficiently long pulse).
2. The switch positions are reversed: the loop switch closes and the RF switch opens. Now the device is a closed loop with gain. The signal circulates through the loop until saturation (unity loop gain) is reached. The loop is held in this position throughout the operation of the ECM system.
3. Output power is continuously coupled from the loop, and the ECM system transmits the pulse back to the threat radar at the instant it is needed for the RGPO process. The coupling position is determined by the requirements for minimum through-time delay (before the delay line) and sufficient power level (after the amplifier).
4. On completion of the RGPO process, the FML is switched back to its "standby" position, ready to memorize another RF pulse.

Storage In An FML

The ideal condition of a storing FML is the saturated state, with one RF signal present experiencing unity loop gain, and no other signals in the loop. Since the loop is an active system, broadband noise is generated, which tends to degrade the loop's performance. Any other signal present (such as unwanted harmonics or mixer products generated somewhere in the ECM system) will likewise decrease the effectiveness of the loop.

Fortunately, when amplifiers are compressed, they exhibit small-signal gain suppression so that signals other than the large, compressing signal suffer decreased gain in the presence of the large signal. This tends to work in favor of the desired FML performance when the RF signal compresses the amplifier. Eventually, the noise suppression breaks down, and the desired signal is defeated in favor of some mixture of signals more suited for storage within the particular FML.

When the energy within some specified bandwidth of the RF input frequency has fallen by some specified amount from its value at the initiation of storage, *storage failure* is said to have occurred. The time at which this happens is defined as the FML's storage time. Figure 3 illustrates a test set-up to observe the gradual failure of an FML in the storage mode. The output of the FML is sampled in one-microsecond steps after the initiation of storage. The energy sampled is sent into a spectrum analyzer and the spectra generated are shown in Figure 4.

Spectrum 1 is the FML signal during the first microsecond of storage. The RF signal frequency is at the center of the horizontal axis, and each horizontal division is 500 MHz. Each vertical division is 10 dB. The energy in the FML during this first microsecond is concentrated very close to the RF frequency.

As the FML stores longer, the quality of the stored signal degrades.[2] Each subsequent spectrum shows a lower signal-to-noise ratio. The noise in the loop gradually grows at the expense of the signal until, in Spectrum 4, there is only a small fraction of the stored energy near the original RF frequency. Noise buildup has caused storage failure.

While noise buildup eventually causes storage breakdown, as illustrated in Figure 4, the problem is partially ameliorated by the use of a channelizer with filters which break the band of interest into narrower sub-bands. Since noise power in the device is proportional to its bandwidth, the channelizer increases the signal-to-noise ratio of the device, enhancing noise suppression and, hence, storage time.

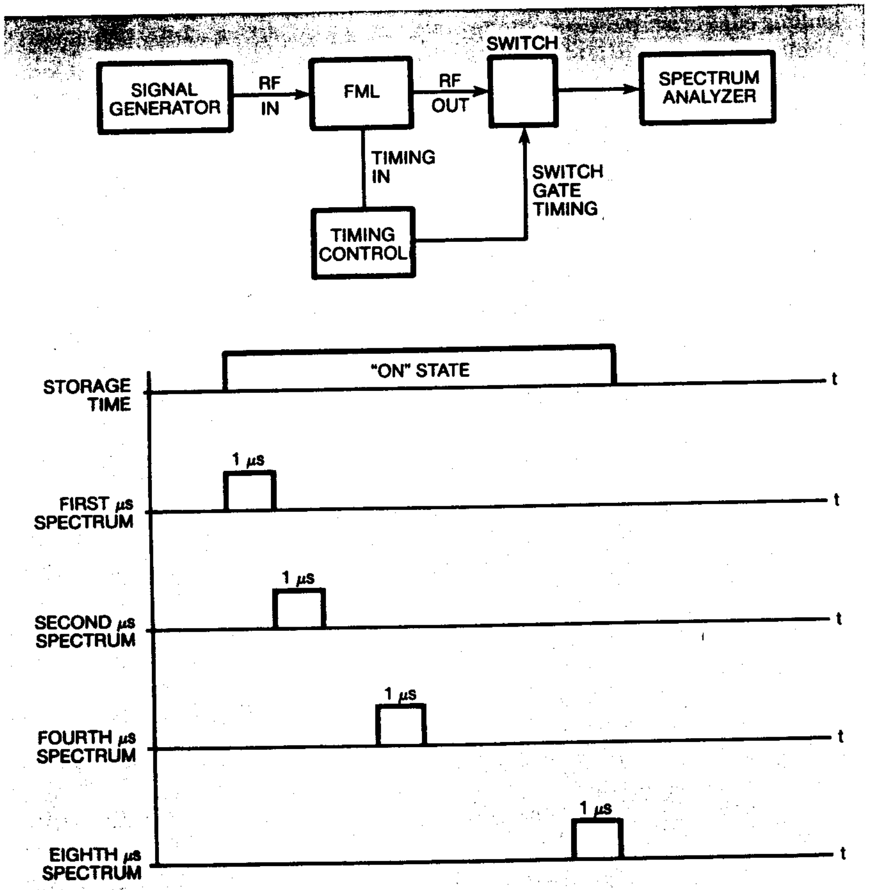


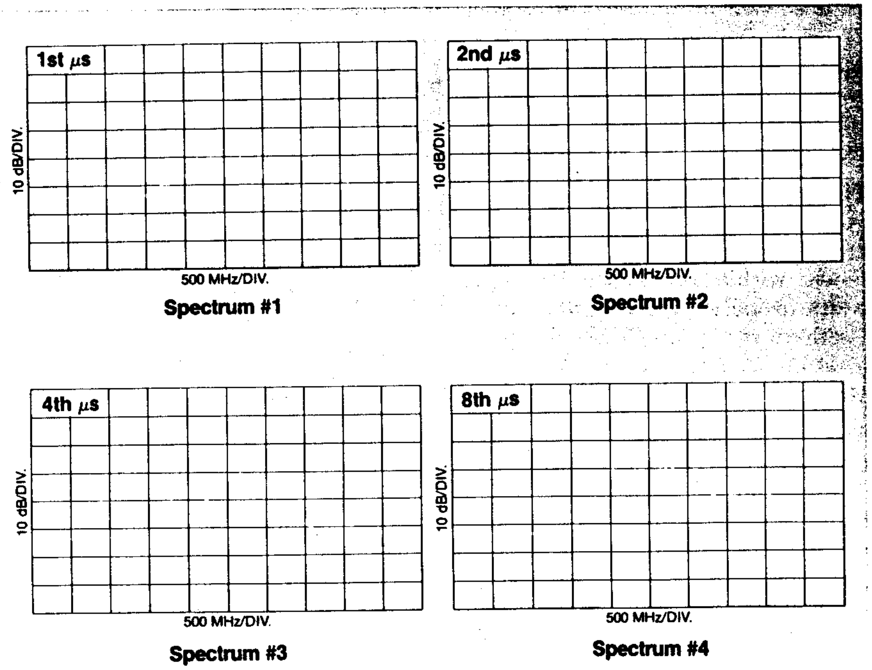
Figure 3. RF output spectrum test set-up and timing.

Figure 5 is a schematic diagram of an FML with a channelizer. The channelizer divides the frequency band into 4 sub-bands, thereby increasing the signal-to-noise ratio of the loop by 6 dB. Channel selection must occur before the leading edge of the RF pulse reaches the channelizer, or some RF is "wasted." To give maximum time for the ECM system to select the sub-band of the signal, the channelizer is usually placed after the delay line.

In maximizing storage time in an FML, the key items are the amplifiers. Good control over FML performance is obtainable with state-of-the-art solid-state amplifiers. Satisfactory results are achieved if the amplifiers exhibit small-signal gain invariant with frequency, and good noise and spurious signal suppression under compression by an in-band RF signal.

Coherency

While storage time is an important measure of the effectiveness of an FML, there is another figure of merit for the capability of the system to work effectively in an ECM system. One can imagine an FML whose spectrum does not change significantly over the desired duration of storage[2], but the spectrum is not sharply peaked at the RF frequency of the input pulse. In this case, the corresponding data in Figure 4 would be four spectra that are all the same, but without a sharp peak at the center. The storage time of such a device would be very long, but the FML would nonetheless be ineffective



Spectrum #1

Spectrum #2

Spectrum #3

Spectrum #4

Figure 4. Spectra of FML output at successively later storage times.

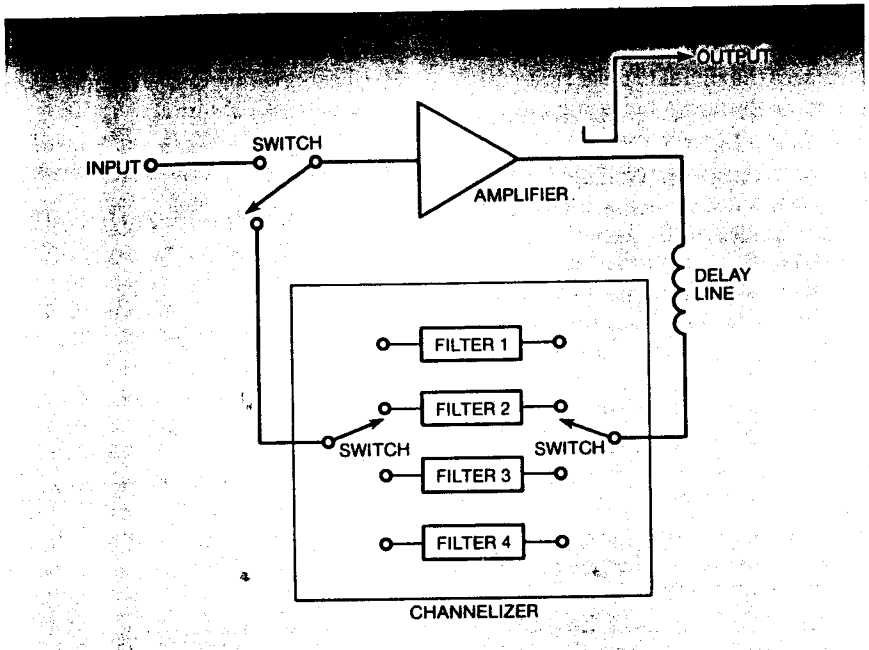


Figure 5. FML with channelizer.

against the threat radar because there would be only a small fraction of the loop energy near the RF input frequency.

The quality missing in such an FML is good coherency. Coherency is defined as the fraction of the total FML output power within some specified bandwidth (usually a threat radar's bandwidth) of the input RF frequency. An ideal frequency memory device has 100-percent coherency (and infinite storage time).

Coherency and storage time are related. The latter is defined as that point in time after the initiation of storage when the power in some specified bandwidth centered on the input RF frequency has decreased by a specified amount from its value at the beginning of storage. Coherency is the instantaneous fraction of energy within the bandwidth. Since the looping amplifiers are saturated during storage, the power circulating through the loop is constant, regardless of its percentage of input RF signal, unwanted RF signals, or noise. Therefore, since the power within the bandwidth of interest decreases with time, but the total power is constant, coherency has fallen by the same fraction as in-band power at the point of storage failure.

Since noise power is always present, it is impossible to have a coherency of 100 percent in an FML. If this were the only limitation on coherency, it would be possible to get very close to perfect performance over wide bands, with proper care, in a low-noise system. Another effect characteristic of recirculating systems, moding, proves to be a more severe limit on achievable coherency in practical systems.

Moding And Fourier Analysis

To determine the frequency spectrum achievable with an FML, analysis of the output wavetrain, in time, must be made.[2] The electric field of a perfect RF input pulse passing any point as it travels by is a segment of a perfect sine wave. If the FML were to store the pulse perfectly and send it back, the returning wave (the output pulse) would be identical to this sine-wave segment.

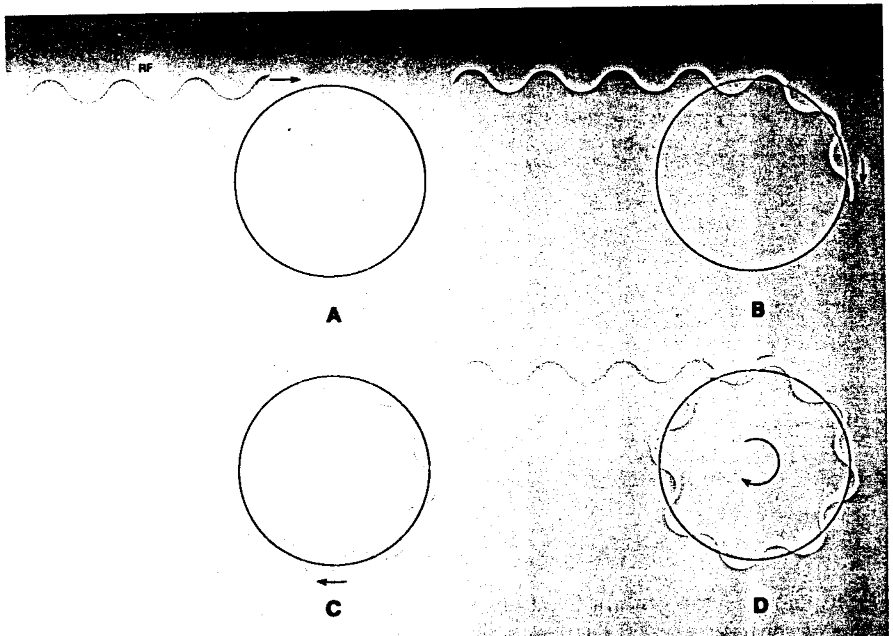


Figure 6. RF wave train filling a loop.

However, this is not what happens when an FML returns an RF signal. As demonstrated in Figure 6, the wave train enters the loop, progressing through. At some point, the wave has travelled all the way around the loop, and reaches the point of entry. At this instant, the loop is "filled" with RF, and the switch is thrown to close the loop. No more RF can then enter the loop, and the wave inside the loop continues to travel; the entire pattern inside the loop rotates clockwise, as shown in Figure 6D. As a result, there is generally a discontinuity in the waveform at the point of entry to the loop. Unless the length of the loop is exactly equal to an integral number of wavelengths of the radiation inside the loop, there is a phase jump at the junction between the leading and trailing edges of the pulse. Frequencies with a perfect match (zero phase error) occur at,

$$N\lambda = LL$$

where, N is any integer, λ is the wavelength of the RF signal inside the loop, and LL is the electrical length of the loop. Such frequencies are called preferred frequencies, or preferred modes.

The RF signal sent through the output port is simply the repeating sample of the electric field of the wave inside the loop. If there is a discontinuity in the field in the loop, the mismatch passes by the output coupler every circulation, and, hence, the output pulse comprises segments of pure RF separated by these discontinuities. Figures 7A, 7B and 7C are time-domain wave trains of a 100-ns loop, with frequencies of RF

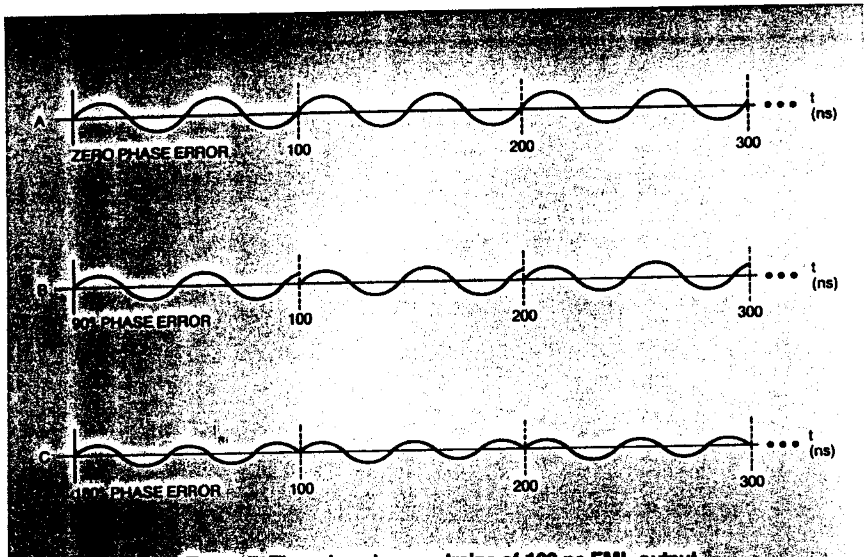


Figure 7. Time-domain wave trains of 100 ns FML output.

input pulses corresponding to a phase error of zero degrees, 90 degrees, and 180 degrees, respectively.

The phase error of the radiation in the loop in Figure 6 has a considerable effect on the Fourier spectrum of the output pulse. Regardless of the frequency of the RF input pulse, the spectrum has peaks at frequencies corresponding to preferred modes. The preferred mode locations are a property of the loop, and are separated by,

$$\frac{V}{LL}$$

where, V is the RF phase velocity and LL is the loop length. The division of energy between the various preferred modes is determined by the location of the input RF frequency, relative to the preferred modes.

Figure 8 shows the spectrum of each of the cases of loop phase error shown in Figure 7. Note that the spectrum in each case peaks in the general area of the RF input pulse, but the actual peaks are always on a preferred mode, and, so, only when the input pulse is at a preferred frequency do the input and output spectral peaks coincide.

Moding clearly has an effect on the coherency achievable with an FML over any useful frequency band. Since the preferred modes are separated in frequency by the reciprocal of the loop length, the longer the loop length, the more densely packed are the preferred modes. As a result, the coherency attainable increases with increasing loop length. For reasons connected with the design of ECM systems, there is an upper limit on the length of delay line that can be used in any given FML, and this is the major limitation on coherency.

Figure 9 is a 3-parameter plot showing the maximum coherency attainable in an FML as a function of phase error and bandwidth. Bandwidth for the plot is measured in units of preferred-mode spacing. The plot illustrates that on any preferred mode (zero phase error), coherency is relatively insensitive to bandwidth (for the range of bandwidths shown), but for the case of a frequency halfway between preferred

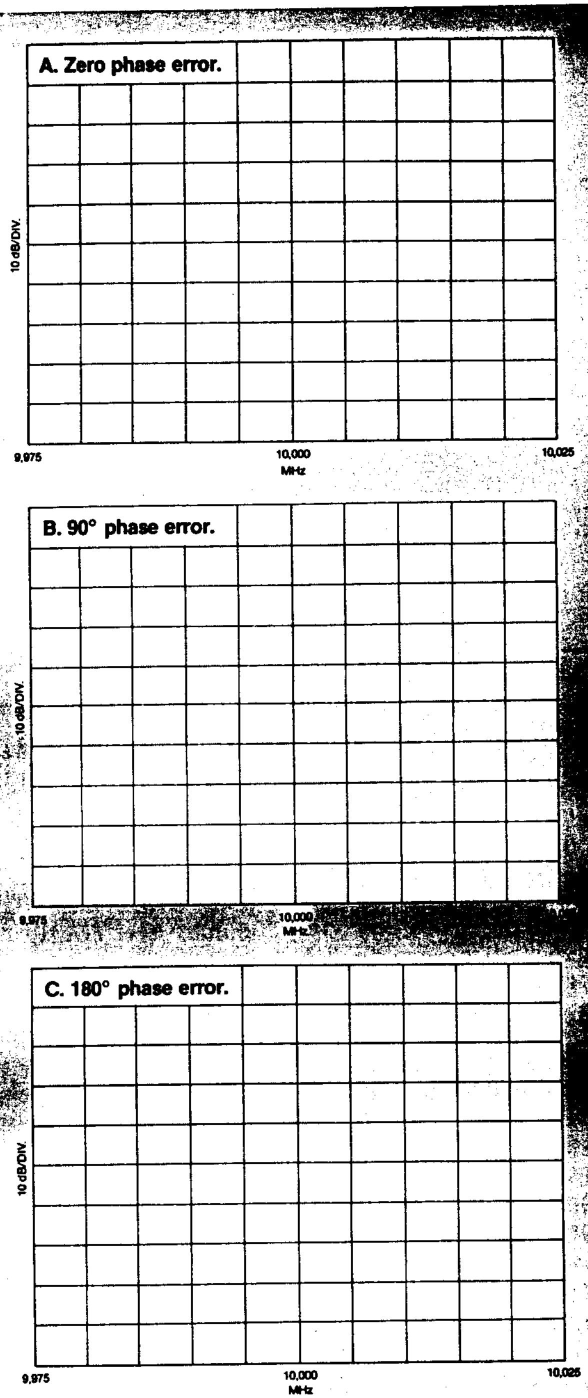


Figure 8. Spectra of FML output for cases of zero, 90° and 180° phase error. (500 ns pulse sample)

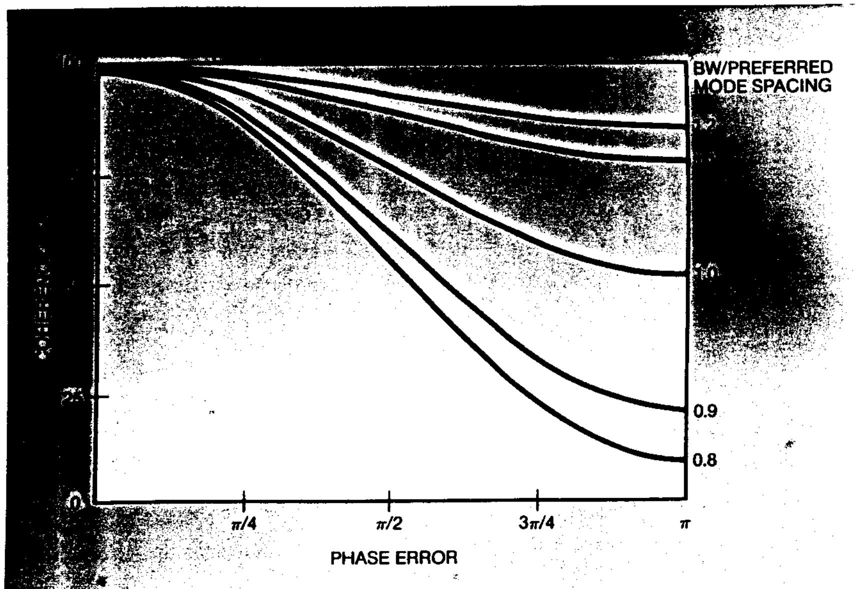


Figure 9. Spectral coherency of FML output vs. phase error.

modes (180 degrees phase error), there is a dramatic difference between the case of a bandwidth slightly less than the preferred-mode spacing, and one slightly greater. For FML design purposes, since there are many preferred modes within the frequency range of the device, the worst case (180 degrees phase error) must be used.

Increasing Coherency With Phase Shifters

The maximum coherency limit imposed by the Fourier spreading of the RF input frequency into the preferred modes of the loop can be extended upward by the use of a phase shifter in the loop. Since phase error is the source of low coherency at non-preferred modes, controlling phase error can enhance coherency of the FML.

An FML with a fixed 180-degree phase shifter is shown in Figure 10. The phase shifter causes the preferred modes of the new loop to be shifted one half-cycle from their positions in the plain loop. The preferred frequencies are now determined by the equation,

$$(N+0.5)\lambda = LL$$

where, the 0.5 represents the contribution of the 180-degree phase shift. The frequency that suffers a 180-degree phase error in a plain FML has zero phase error in the FML with the phase shifter: it is exactly on a preferred mode.

Phase shifts of other than one half-cycle (180 degrees) can be introduced into the loop, and their effect is to shift the position of the preferred modes by an amount corresponding to the phase change introduced. As the phase change introduced into the loop is increased, the positions of the preferred modes move sequentially, but their spacing (corresponding to the loop length) remains the same.

Since the fixed phase shifter described above does not decrease the spacing of the preferred modes in the FML spectrum, it does not increase coherency over a large frequency band: it merely shifts the problem spots of low coherency in frequency. However, by properly controlling a phase shifter, it can be used in either of two ways to raise the coherency of an FML.

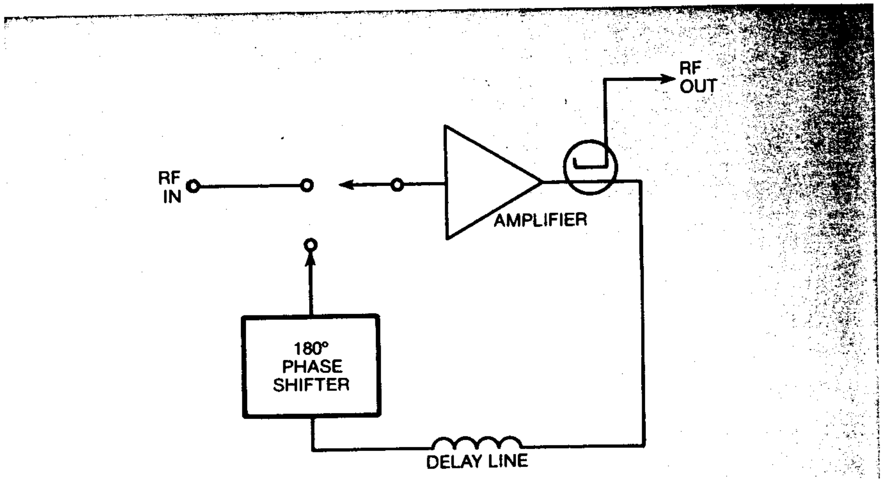


Figure 10. FML with fixed 180° phase shifter.

The simpler use of a phase shifter in an FML is the free-running phase shifter. In this scheme, while the ECM system is running, a phase shifter in the FML is repeatedly switched between some number of equally spaced states between 0 and 360 degrees. Typically, two states are used: 0 and 180 degrees. The shifting is generally done in some random fashion to keep it unpredictible. A threat radar uses many radar pulses for its information, and the spectrum that the radar sees is a superposition of the spectra corresponding to each phase state. Since the FML spends an equal amount of time in each state, the spectra are equally weighted at the output. Thus, the input RF frequency in such an FML is never more than ¼ of the original mode spacing away from a preferred mode. (In a plain FML, it can be ½ a spacing from the nearest preferred mode.) Coherency within a bandwidth less than the original preferred mode spacing is improved dramatically at worst case. Figure 11 shows the spectrum of an FML with such a phase shifter. The spectrum is a superposition of those in each phase state, i.e. Figures 7A and 7C.

In Figure 11, one of the phase-shifted states places the RF frequency exactly on a preferred mode, and the other is halfway between preferred modes. In this particular situation, outside the central three peaks in the spectrum, only one set of preferred modes is visible because of the lack of moding in a preferred-mode spectrum (see Figure 7A).

There is a limit to the coherency that can be gained with a free-running phase shifter. The free-running phase shifter adds preferred modes to the FML spectrum, but most of these modes (all but the mode nearest to the input RF frequency) are outside the bandwidth of interest. The energy in the central mode introduced by the phase shifter increases coherency, but the energy in the outer modes actually works in the opposite direction. A better situation would result if one could insert only the preferred mode nearest to the input RF frequency. Even better results would be

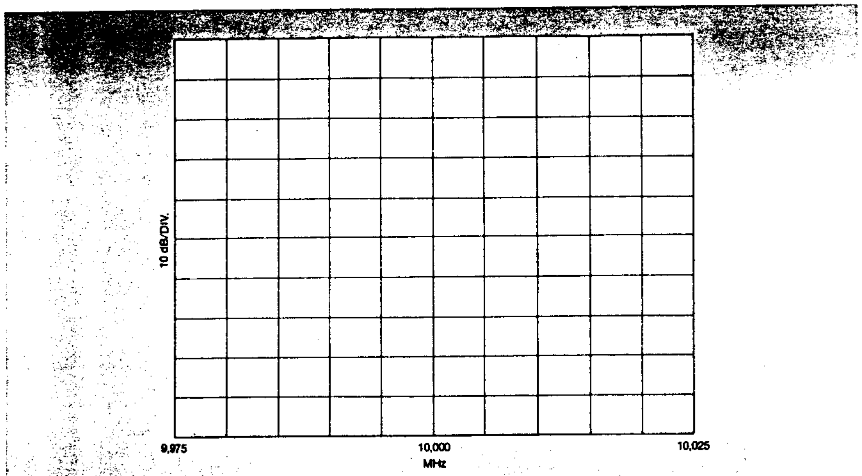


Figure 11. Spectrum of FML in Figure 7 with free-running, two-state phase shifter. (Spectrum is a superposition of Figures 7A and 7C.)

obtained if the loop could be actively changed to position the preferred modes of the original loop to force one mode to coincide (or nearly coincide) with the input RF frequency.

This more sophisticated use of the phase shifter is called *active phase shifting*. Its implementation is substantially more complex than free-running phase shifting. The phase of the RF signal at two electrically adjacent points in the loop, the start and the end, is sampled, and the phase change around the loop is determined by electronics. Then, a phase shifter is switched to give the proper phase length to the loop to keep the signal within some specified distance from a preferred mode. Thus, the recirculating pulse sees a loop that is tailored to its specified frequency to give a high coherency to the output signal.

Figure 12 shows, in block diagram, an example of an active phase shifter being constructed at W-J. For this particular case, the phase compensation is chosen as one of four states, keeping the recirculating pulse within 45 degrees of a preferred mode.

A Real FML

Actual FMLs are somewhat more complicated than the block diagrams presented so far. Typically present are several looping amplifiers, input and output amplifiers, equalizers, temperature compensation circuits, channelizers, phase shifters, integrated circuits and switches for control, and various passive microwave devices. Figure 13 shows an FML intended for airborne applications. The unit utilizes thin-film technology to increase packing density of the components. It has a free-running phase shifter and a channelizer, and stores for a minimum of 3 μs over a wide temperature range and frequency band.

Future Memory Devices

The limitations on the performance of the FML described above are the theoretical limit on coherency, the practical limit on storage time, and the inherent inability of a recirculating pulse system to respond to a frequency modulated pulse. The loop can only store at one frequency (more accurately, one set of preferred mode amplitudes)

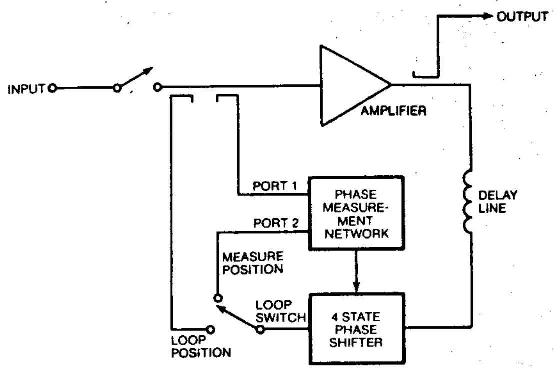
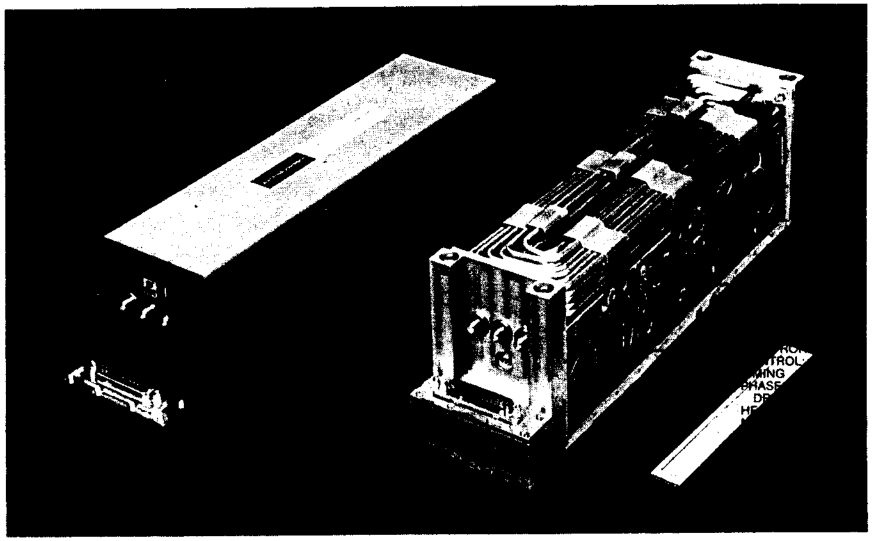


Figure 12. FML with four-state active phase shifter.



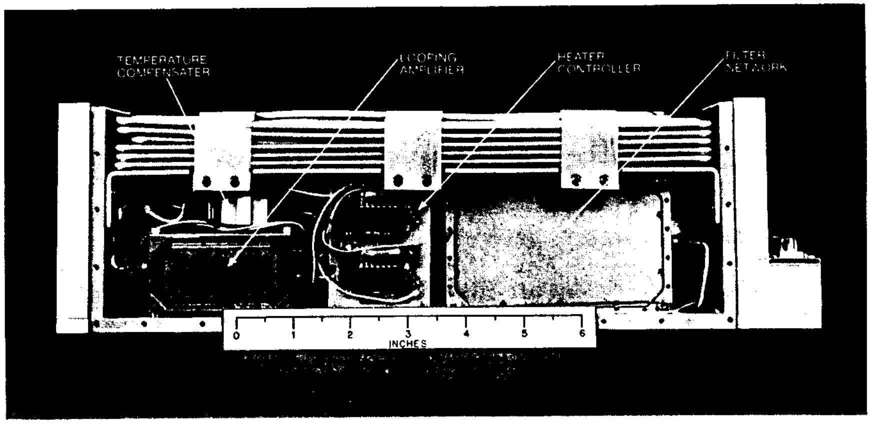


Figure 13. Airborne FML.

at a time. If the frequency of the pulse were changing with time, the loop would store one frequency, and suppress others. Ideally, what is needed is a device that characterizes an input pulse of RF energy, and sends back an exact replica at some delayed time. Work is progressing on several systems to approach this goal.

A digital memory is a device that receives an incoming pulse, does whatever conversions are necessary, and, in some manner, digitally stores the information necessary to recreate the pulse later. This memory has essentially infinite storage time, because once the information is stored in the memory, it need not be tampered with until the next pulse to be memorized arrives. Such a system represents an immense improvement for memory-type ECM systems.

Fiber-optics constitutes another area of current research for memory systems. Kilometers of light-conducting fibers can be compressed into extremely small volumes. RF is used to modulate the light, and the light pipe is made so long that no recirculations are necessary: the length is the maximum storage time multiplied by the speed of light. The output is tapped at steps along the fiber, corresponding to various delay times. In this way, a faithful reproduction of the input pulse is generated at delayed intervals.

Both of these technologies are much newer than FMLs, and both are likely to be more expensive when implemented commercially. Based on the current and future threats in the field, FML systems in their current form will still be used extensively for years to come.

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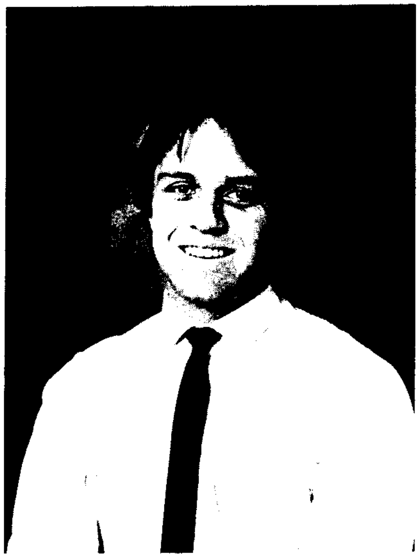

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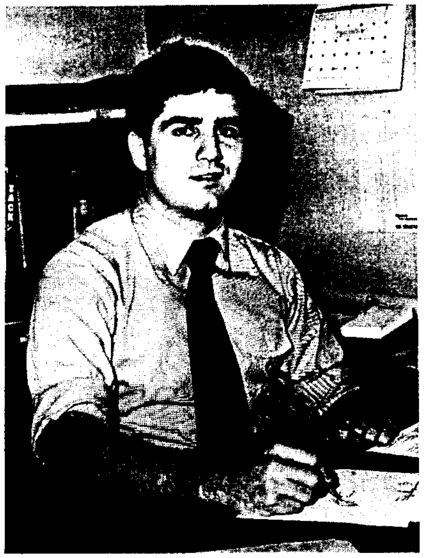

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