IV. Conclusion

The experimental results obtained with a large number of filters prove that the high quality of SAW filters developed in the laboratory can be realized also for larger production quantities. SAW filters are promising alternatives for phased-array radar applications. They improve not only the single-receiver performance by realizing almost ideally the matched filter concept but also the array performance by the excellent reproducibility of the frequency response and by the stability of their parameters.

Acknowledgment

The authors would especially like to thank A. Smith for producing most of the SAW filters, E. Schlack for the dielectric film trimming of the filters, F. Rodermund for developing the filter modules, and J. Rüdiger for technical support. Thanks are also due to B. Dischler and P. Hiesinger for theoretical calculations.

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Use of an SAW Multiplexer in FMCW Radar System

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***Abstract*—This paper describes the application of an SAW multiplexer to develop range line resolution in FMCW millimeter-wave radar systems. The basic system design concept as well as test results are presented describing the function of the SAW multiplexer in developing the multiple-range cells in the millimeter-wave terminal guidance seeker. The SAW multiplexer has 16 channels and uses the offset multistrip coupler technique for sorting the acoustic beam into various acoustic tracks according to frequency.**

I. Introduction

RANGE RESOLUTION in FMCW radar systems has been achieved using multichannel surface acoustic wave (SAW) filter devices. This paper describes the basic system design concepts employed for developing range cells in linear FMCW radar using the SAW filters. The techniques discussed are currently being used in low-power solid-state millimeter-wave radar for air-to-ground terminal guidance of antiarmor munitions. The narrow-band SAW filters are incorporated in the receiver IF sections where each filter represents a range cell that is dimensionally proportional to range. The small size, light weight, low power consumption, and stable performance characteristics make the SAW filter an ideal choice for missile seeker applications.

Manuscript received February 4, 1980; revised July 22, 1980.

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II. FMCW Technique

In a linear frequency-modulated continuous-wave (FMCW) radar [1], [2], the transmitter generates a periodic waveform having a linearly varying frequency versus time for each modulation sweep period. The frequency-modulated signal is transmitted from the radar antenna to the target where a portion of the signal is reflected back to the radar. The frequency of the return signal received by the antenna is compared with a sample of the instanta-

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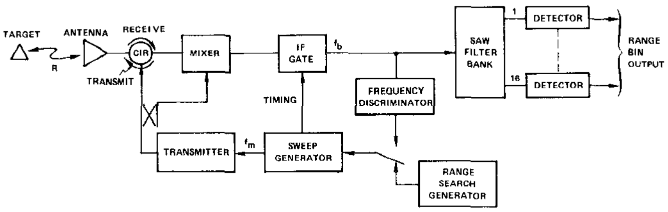

Fig. 1. Block diagram of the FMCW radar system.

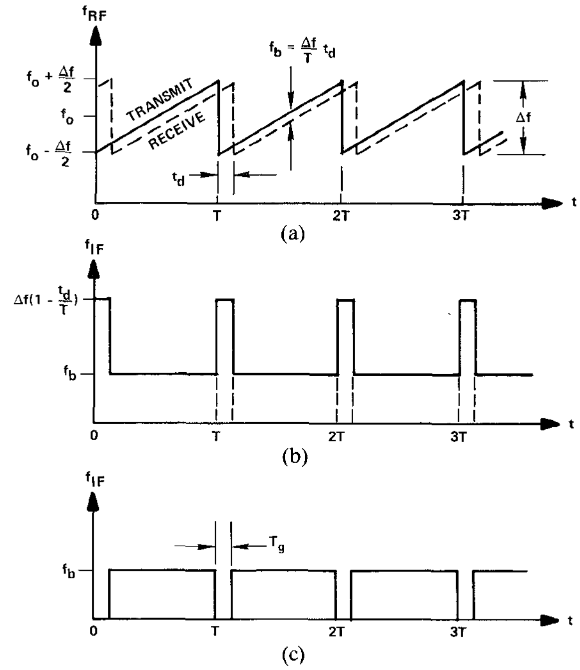

Fig. 2. FMCW radar frequency waveforms. (a) Frequency–time delay for FMCW radar transmitted signal and received signal. (b) Difference frequency in IF circuits without gating. (c) Difference frequency in IF circuits with gating.

neous frequency of the transmitter signal to derive a difference frequency f_b, shown in the block diagram of Fig. 1.

It is customary to analyze the behavior of an FM system geometrically using the time–frequency diagram as shown in Fig. 2. The transmitter periodic RF sweep covers a frequency band Δf centered at a nominal radar carrier frequency, f_0. In Fig. 2(a) the solid-line sawtooth waveform represents the deviation of the transmitter frequency, while the dashed line represents the received frequency delayed by transit time t_d. The transit time is dependent upon the velocity of propagation and the range to the target and is related to these parameters by

$$t_d = \frac{2R}{C} \tag{1}$$

where R is a target range and c is the velocity of light. The effect of the transit-time delay is to shift the received signal along the time axis causing a difference to exist between the transmitted and received frequencies at any instant in time t. This difference frequency, shown in Fig. 2(b), is called the intermediate frequency or beat frequency f_b.

The amount the transmitter changes while the wave travels to the target and back is proportional to the rate of change of transmitter frequency multiplied by the transit time; therefore, over most of the sweep period T, the frequency of the IF signal or beat frequency f_b is

$$f_b = \frac{\Delta f \cdot t_d}{T}. \tag{2}$$

Usually the sweep period is selected to be much larger than delays of interest due to target signals; that is, $T \gg t_d$, and the portion of time for which the difference frequency is $\Delta f - (\Delta f \cdot t_d / T)$ is small and generally of no interest. The IF signal during these times can be gated out as shown in Fig. 2(c), where $T_g \geqslant t_d$. The duration of the IF pulse having frequency f_b then becomes $T - T_g$.

Since the modulation waveform is periodic with a time period T, the frequency of modulation f_m is then

$$f_m = \frac{1}{T}. \tag{3}$$

By substitution of (1) and (3) into (2) we have

$$f_b = \frac{2R\Delta f \cdot f_m}{c} \tag{4}$$

which is the basic equation used for analysis of linear FMCW radar systems.

From (4) we can see that if the modulation frequency f_m and the transmitter deviation Δf are held constant then small changes in range R result in small changes in the beat frequency f_b. Therefore, by using a bank of narrow-band IF filters centered around the nominal beat frequency we can define range cells in the radar beam.

By rearranging terms in (4), we have

$$R = \frac{f_b c}{2\Delta f \cdot f_m}. \tag{5}$$

From this equation we can see that if the beat frequency f_b and the transmitter deviation Δf are held constant then the range R to the target is inversely proportional to the modulation frequency f_m. Therefore, range to the target can be determined by measuring the modulation frequency. Range search and acquisition are achieved by changing the frequency of the sawtooth modulation signal until a return signal is received from the target at the selected IF frequency. A frequency discriminator then provides range tracking by controlling the modulation frequency. Implementation of these concepts in the FMCW radar is shown in the system block diagram in Fig. 1.

III. Range Resolution

The bandwidth of the IF signal and the characteristics of the narrow-band IF filters are important considerations in determining the radar system range resolution where resolution is the ability of the system to separate the returns from targets at different ranges. This ability will be enhanced if the target return signal at IF has the narrowest possible bandwidth and the bank of narrow-band filters has equivalent performance characteristics. Important considerations for spectral purity of the return signal at IF are transmitter sweep linearity and transmitter FM noise.

Important considerations for the narrow-band filters are

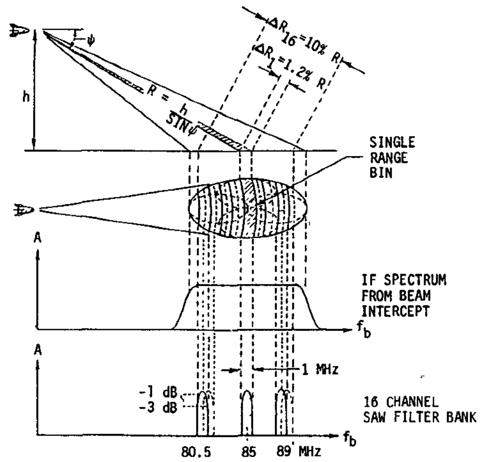

Fig. 3. FMCW multiple-range cells.

center frequency, bandwidth, shape factor, ripple content, and frequency stability.

In choosing the narrow-band filters, one needs to consider the possible filter types and characteristics that are appropriate for the application. Possible filter types for the FMCW radar application include *LC* filters, crystal filters, and SAW filters. The specific application discussed in this paper is for millimeter-wave guidance of air-to-ground antiarmor munitions where size, weight, cost, and reliability are other important factors in making the filter selection.

The filter center frequency is determined by the transmitter frequency deviation, desired operating ranges, and modulation rates consistent with linear waveform development. Typical filter center frequencies are in the range from 30 to 200 MHz. The range resolution is proportional to the ratio of the filter bandwidth to the filter center frequency; therefore, fractional bandwidths on the order of 0.1 to 5 percent are needed. Considering the desired center frequency and the fractional bandwidths required, it becomes very difficult to achieve the performance characteristics with *LC*-type filters. Crystal filters provide the fractional bandwidths; however, they are limited to the lower center frequencies. Another factor to consider is size or space required for a multiple-channel narrow-band filter bank. The SAW filter results in a major space savings as compared to the *LC* or crystal filter approach. Other advantages of the SAW filters besides small size, fractional bandwidths, and frequency range are reproducibility, reliability, and relative frequency stability between individual filters in the filter bank.

Fig. 3 illustrates the formation of 16 range cells in a millimeter-wave FMCW radar using a multichannel SAW filter. In this illustration, the millimeter-wave radar is carried in a missile and the conical scanned antenna is pointed toward the ground at a fixed depression angle. The 16 range cells are shown spaced along the length of the antenna beam intercept on the ground. The IF spectrum received from the beam intercept is centered at 85 MHz. The range bins are formed by using 16 individual filters, each having a 3-dB bandwidth of 1 MHz. The filters are spaced at 0.5-MHz intervals and cover the frequency range from 80.5 to 89 MHz. These filters represent 16 individual range cells, each having a width that is 1.2 percent of range. Since the filters overlap at the 1-dB point, the total range coverage is 10 percent of range.

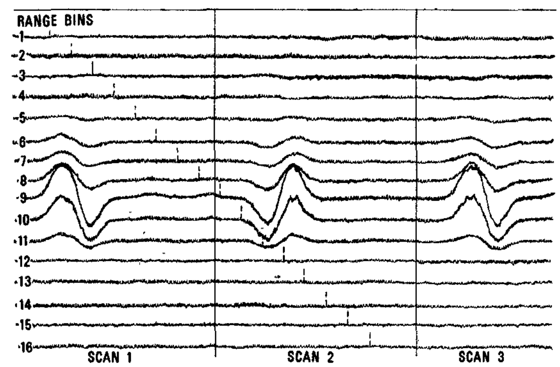

Fig. 4. Typical output signals from the 16 range bins.

The data shown in Fig. 4 illustrate the range resolution of a linear FMCW millimeter-wave radar using the 1.2-percent range cells previously described. In these data, the radar antenna is scanned at azimuth across a point target located between range cells 9 and 10. Scan 1 displays a left-to-right azimuth scan across the target while scan 2 is a right-to-left scan and scan 3 is a repeat of scan 1. The signal shown is the demodulated azimuth error signal or *S* curve developed from the conical scanned beam. Since the IF filters overlap at the 1-dB point, the signal from the target can be observed in adjacent range cells.

As previously noted, the IF signal bandwidth and the IF filter characteristics are the determining factors for range resolution in linear FMCW radar systems. With diligent attention to the linearity of the FM sweep and the SAW filter design characteristics, range resolutions of 0.5 to 0.1 percent can be realized for FMCW systems.

IV. The SAW Multiplexer

The SAW multiplexer which provides the frequency filtering for the 16 range bins uses the offset multistrip coupler (MSC) technique [3], [4]. This technique performs true frequency division multiplexing rather than power division; i.e., instead of dividing the power by 16 and directing the full frequency spectrum to each filter, the offset MSC structure sorts the acoustic signal into various channels according to frequency. Each frequency channel is then detected by a narrow-band output transducer. The MSC structure performs a filtering operation which is essentially $(\sin x)/x$ and this is cascaded with the bandpass response of the output transducer to give added out of band rejection.

The operation of the MSC multiplexer is based on the fact that a signal transferred by a normal MSC from one track to another has a 90° phase advance over the signal remaining in the original track. Conversely, when two signals in adjacent tracks have a 90° phase shift relative to each other, the signal emerging from the MSC will be completely in one track only (assuming the number of

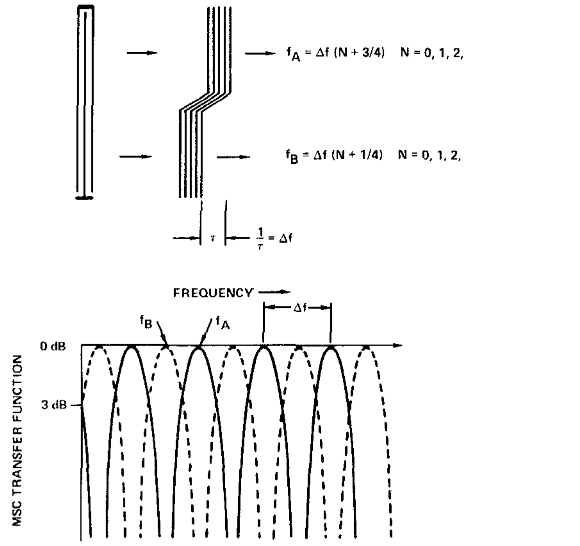

Fig. 5. Frequency response of the offset MSC. The solid line is for Track A and the broken line for Track B.

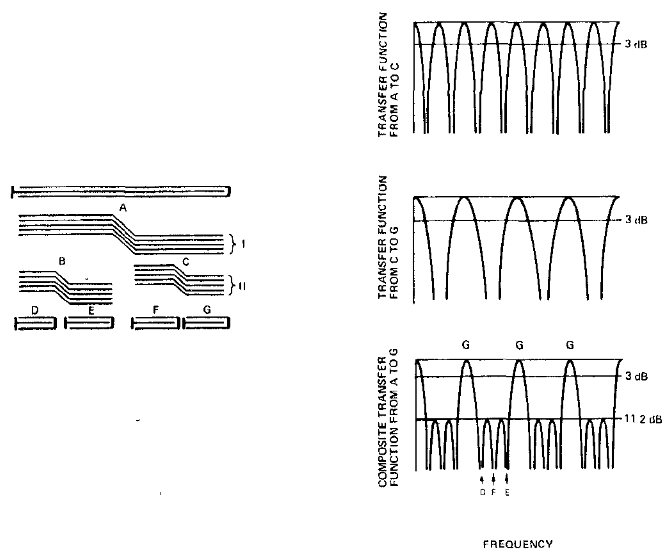

Fig. 6. Schematic of the four-channel MSC multiplexer together with the predicted transfer function.

strips in the MSC is $N_T/2$, where N_T is the number required for full transfer). Without violating this principle, the phase shift can be built into the MSC by incorporating an offset in the MSC as is shown in Fig. 5. Thus the energy impinging on the offset MSC will emerge from either the upper track or the lower track, depending on the degree of offset and the frequency of the signal. The offset MSC with $N_T/2$ strips is the basic element in the multiplexer. To first order, the response of the offset MSC is specified by Δf, where Δf is the separation of the maxima in one channel. Δf is equal to $1/\tau$, where τ is the delay time of the offset.

To obtain a more complete frequency separation, various MSC's with successively smaller offsets are cascaded as shown schematically in Fig. 6. The frequency response of MSC I between ports "A" and "C" is shown in Fig. 6(a). The frequency response of MSC II between "C" and "G" is shown in Fig. 6(b). The offset of this MSC is about half that of MSC I, so that the frequency separation is approximately $2\Delta f$. These two elements are cascaded and their composite response from A to G is shown in Fig. 6(c). The response from A to any one of the other output transducers (A to F, A to E, and A to D) is exactly the same as shown in Fig. 6(c) except for a translation along the frequency axis.

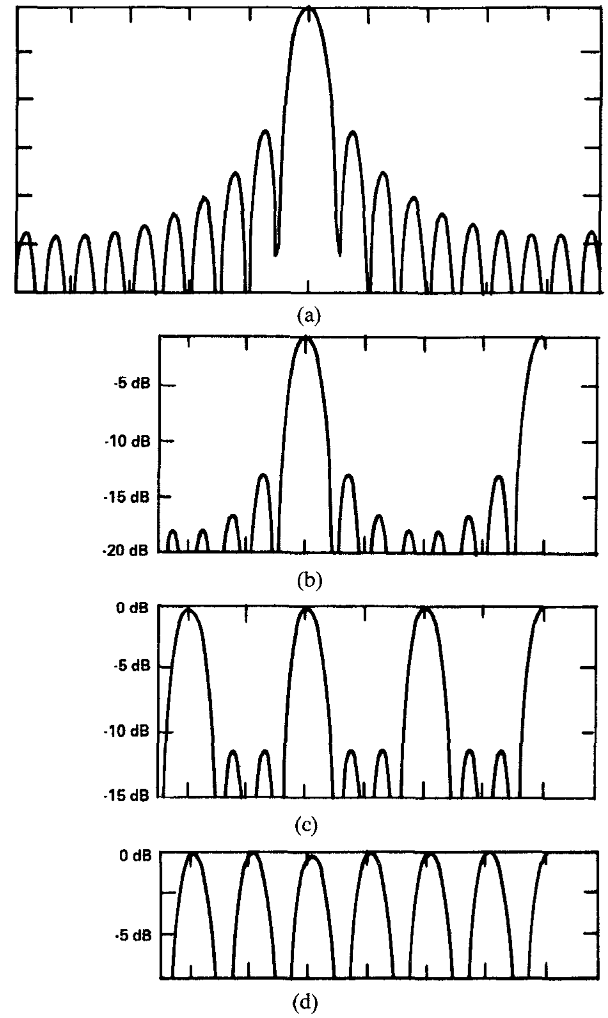

Fig. 7. Response through successive cascaded offset MSC's: (a) through a single offset MSC, (b) through two, (c) through three, and (d) through four.

The offset MSC's may be further cascaded. Fig. 7(a)–(d) shows the response of a surface wave after passing successively through 1, 2, 3, and 4 cascaded offset MSC's, respectively. It is clear that after a few stages the near-in response closely resembles a $(\sin x)/x$.

A schematic representation of the 16-channel multiplexer is shown in Fig. 8. The input transducer which is in the center of the pattern launches a surface wave in two parallel acoustic tracks. The offset between the two active sections of the transducer serves two purposes. It shares the amount of offset required by the first stage's offset MSC so that the connecting lines in the latter element need not be so long, and secondly, it provides an inactive or acoustically nonsynchronous region between the two tracks corresponding to the acoustically active region of the first stage offset MSC connecting lines; i.e., energy is not being directed toward the slanted lines of the offset MSC. The input transducer is bidirectional. This is necessary because

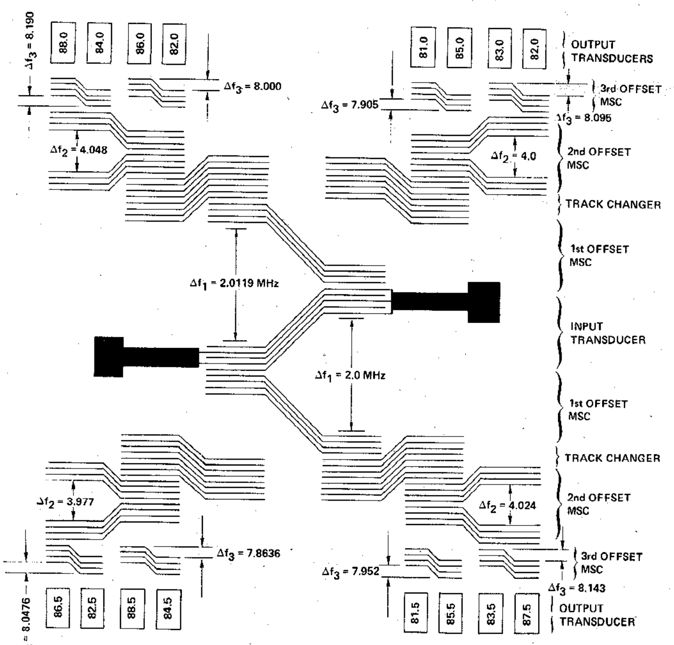

Fig. 8. Schematic of the 16-channel MSC multiplexer.

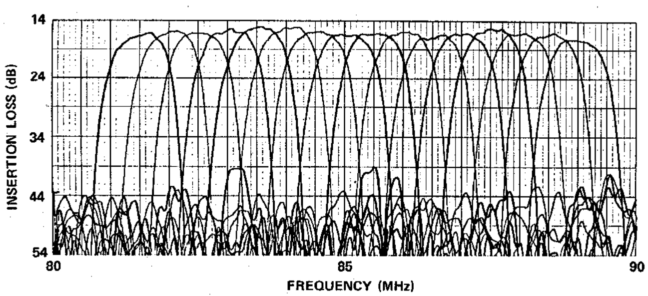

Fig. 9. Output of the 16-channel MSC multiplexer.

the system requires that any frequency must simultaneously appear in three adjacent output channels. As can be seen in Fig. 5, the bandwidth of each channel is sufficiently narrow that any frequency component can appear in at most two adjacent channels. The input transducer in Fig. 8 acts as a simple two-way power divider, driving two interleaved, 8-channel multiplexers which are translated in frequency by $\Delta f/4$. The 3-dB bandwidth of each channel is 1 MHz, but the channels are separated by only 0.5 MHz, and each frequency appears in at least three adjacent channels as required. It may be noticed in Fig. 4 that the pulsed RF appears in 6 channels rather than only 3. This is a consequence of the bandwidth of the input signal which is around 1.5 MHz and, thus, is spread over more channels than a single spectral line.

The composite frequency response of the 16-channel multiplexer is shown in Fig. 9. The substrate is YZ $LiNbO_3$. A high coupling substrate such as $LiNbO_3$ is required in order to keep the number of electrodes in the MSC's from becoming unreasonably large. Each MSC, except the track

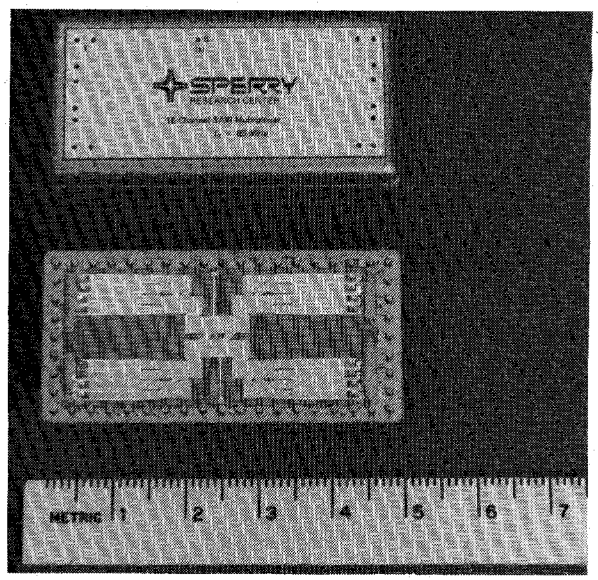

Fig. 10. 16-channel MSC multiplexer.

changer, has $N_T/2$ electrodes which, for an offset MSC on YZ $LiNbO_3$, is approximately 60. The output transducers are apodized with the active taps being staggered across the beam width for more uniform sampling of the acoustic beam. The input transducer is tuned with a series inductor. When the output transducers are untuned, the insertion loss in each channel is 16 dB. A photograph of the 16-channel multiplexer mounted in a flatpack is shown in Fig. 10. The tuning inductor for the input transducer may be mounted inside the flatpack making the unit self-contained.

V. Conclusions

A method for obtaining range resolution in linear FMCW radar systems using SAW filters has been discussed. Range cell widths on the order of 0.5 to 0.1 percent of range can be realized in the FMCW system; this is comparable to the range resolution of a pulsed radar system, yet it maintains the distinct advantage of high average received power inherent in the FMCW radar design. The multichannel SAW filters provide individual cells within the radar antenna footprint. This improved resolution, reduces the amount of signal received from a clutter background, and enhances the ability of the radar to detect targets within that clutter environment. The radar design approach discussed is of particular interest in development of millimeter-wave terminal guidance seekers for antiarmor munitions.

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