PRACTICAL ASPECTS OF SURFACE ACOUSTIC WAVE OSCILLATORS

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ABSTRACT

A SAW delay-line integrated with a thin film amplifier can form the basis of a small, high stability, microwave oscillator. Practical aspects of delay-lines and the noise properties, stabilisation, frequency setting and modulation of oscillators are presented.

Introduction

The SAW oscillator has a stability comparable to that of a bulk crystal locked oscillator but since it can operate at a very much higher frequency, problems associated with harmonics, when deriving higher frequencies by frequency multiplication, are therefore reduced. It can also be frequency modulated. Compared to a phase-locked oscillator it has a wideband low noise spectrum. The SAW delay-line can readily be integrated with a thin film amplifier to form a small high stability oscillator, at present at frequencies up to approximately 1.5 GHz. Therefore the potential of SAW oscillators is attractive and they are now being considered for communications and navigation systems for both transmitter sources and receiver local oscillators.

In this paper it is intended to outline the basic principles and performance of SAW oscillators and the factors affecting the frequency stability, both over an operating temperature range and in the long term, the oscillator single sideband noise, the accuracy of frequency setting and the deviation and maximum rate of frequency modulation.

A SAW oscillator[1] is basically an amplifier with a multi-wavelength surface acoustic wave delay-line path from output to input (Figure 1). The low velocity of the SAW makes it ideal as a delay-line suitable for integration with other thin film components. The upper frequency is limited by photolithography techniques; e.g. with $\lambda = 3.2$ μm at approximately 1 GHz line widths of 0.8 μm need to be defined in the transducer metal pattern.

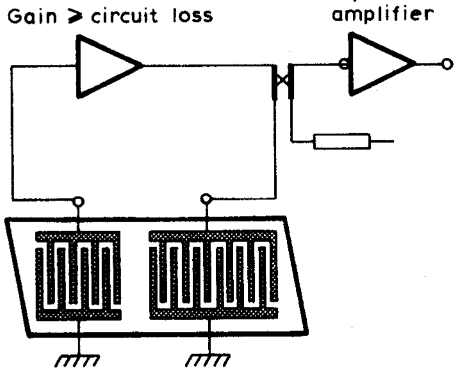

Fig. 1 SAW oscillator

Conditions for oscillation

The gain of the amplifier must be greater than circuit losses. In practice, at UHF, loss of the delay-line with both transducers power matched, is typically 17 dB. Some power is extracted by the load, so a typical amplifier gain might be 24 dB, allowing excess gain.

The oscillation frequency must satisfy the condition:

$$2n\pi = 2\pi f \frac{l}{v} + \phi_e \qquad \ldots(1)$$

where n is an integer
l is the SAW line length
v is the velocity
and ϕ_e is the remaining loop phase shift.

Assuming the delay-line is stable the frequency deviation is therefore:

$$\Delta f = -\Delta\phi \frac{v}{2\pi l} \qquad \ldots(2)$$

The oscillator stability increases with greater length, l, giving a large value of n. As n is increased the frequency separation between possible modes of oscillation decreases i.e. $f_{n+1} - f_n = f_n/n$. For most applications it is necessary to limit the oscillator to a single mode and the delay-line is therefore designed to have a narrowband filter characteristic.

Oscillator noise

The plateau noise of the oscillator, away from the frequency where the filter characteristic of the SAW delay-line has any influence, is the amplifier output noise. This is approximately:

$$N_p = 10 \log_{10}\left[\frac{G^2kT_oF}{P_o}\right] \text{dBc/Hz} \qquad \ldots(3)$$

where G^2 = the power gain of the amplifier
F = the operational noise figure
P_o = the amplifier saturated output power
dBc = dB relative to P_o (the carrier power)

In practive the source impedance will be a large mismatch and would be purely reactive but for circuit and transducer losses. It is possible to show that the noise power output is reduced under these conditions. Further, the gain of the amplifier, at the oscillation frequency is compressed to equal the circuit loss and the small signal gain is compressed by a greater amount. Hence the qualification that equation (3) gives the approximate value, which should be better in practice.

The single sideband FM noise at offset $\Delta\omega$, relative to carrier power is given by:

$$F_{ssb} = 10 \log_{10}\left[\frac{G^2kT_oF\omega_o^2}{4Q^2P_o\Delta\omega^2}\right] \text{dBc/Hz} \qquad \ldots(4)$$

where $2Q = \omega_o\tau = 2\pi n$ (τ is the delay)

From the equation (4) it is apparent that the lowest noise performance will be obtained if the delay-line loss is minimised and a low noise, high power amplifier is used with a long delay-line. However the tuning range, which can be achieved by external phase shift, given in equation(2), is inversely proportional to length.

Equation (4) has been derived in terms of the noise power kT_o from a resistor and differs from that of Lewis[1], who has a factor $4kT_o$.

The noise performance of an oscillator is shown in Figure 2.

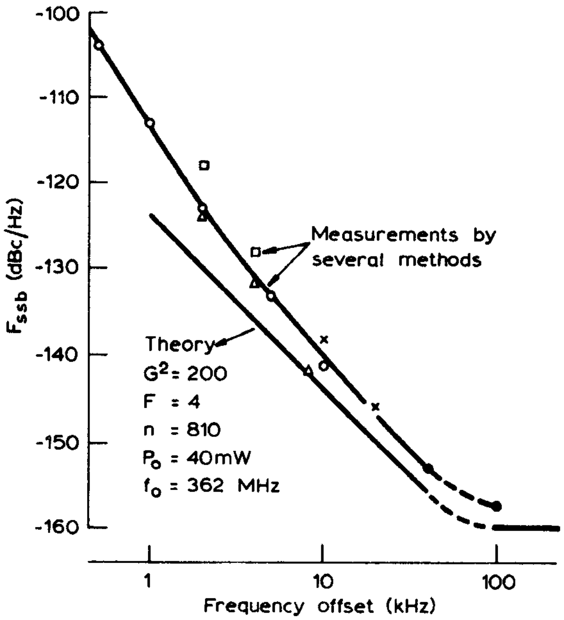

Fig. 2 SSB phase noise of typical SAW oscillator

Filter design and construction

The surface acoustic wave is launched in the piezo-electric material by transducers of a thin metal film interdigital structure where common polarity fingers are a wavelength apart (Figure 1). The filter characteristic is obtained by designing on the principles of an interferometry array. A long transducer is required to give a narrow bandpass characteristic. A transducer mechanically loads the surface and causes attenuation and slowing of the wave. Further, loading of the surface causes reflections within the transducer which distorts the passband[2]. This is minimised by thinning the structure which has the added advantage of giving less slowing and attenuation of the wave. This structure (Figure 3a) gives a comb of frequencies, as indicated in Figure 3b. The other transducer is designed to select a frequency of the comb and give nulls at the remainder as shown by the dashed curve. For a lossless structure the delay-line length is between transducer centres. Multi-frequency operation has been demonstrated by selecting other frequencies of the comb by placing additional transducers at both ends of the ladder transducer and then electronically switching.

In practice a spread of the delay is found in production at higher frequencies due to the phase centre of transducers not being at the physical centre because of imperfections and attenuation under the length of the transducer. This shortening of the delay-line has been measured at 400 MHz to be approximately 7%. The photograph (Figure 5 - on the next page) shows the transient response of this delay-line with 10 rungs in one transducer and 2 rungs in the other. This shows rung imperfections and an attenuation of approximately 0.5 dB per rung spacing. At 1 GHz this shortening of the delay-line is greater.

Ageing is currently between 1 and 10 ppm/year. This and further improvements are dependent on surface finish and cleanliness and the sealing in a dry nitrogen atmosphere.

The simple equivalent circuit of an interdigital transducer (IDT) at 1 GHz is shown in Figure 4a. This gives an impedance plot (Figure 4b) approximately fitting the measured impedance.

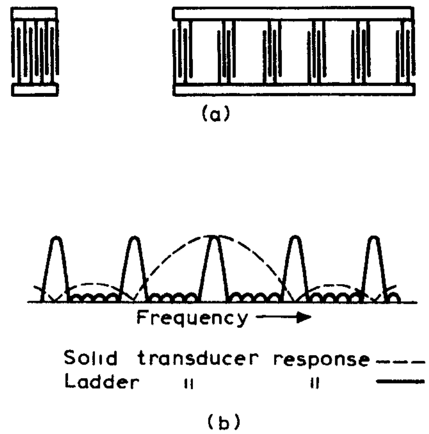

Fig. 3a) Delay-line with ladder transducer
b) Frequency response

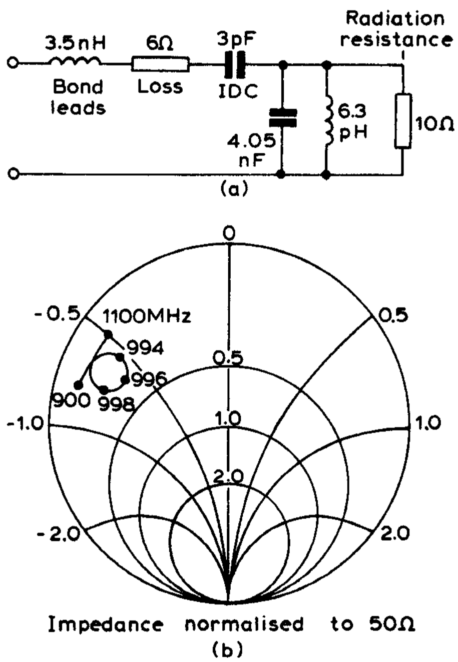

Fig. 4a) Equivalent circuit of IDT
b) Impedance locus 900 to 1100 MHz

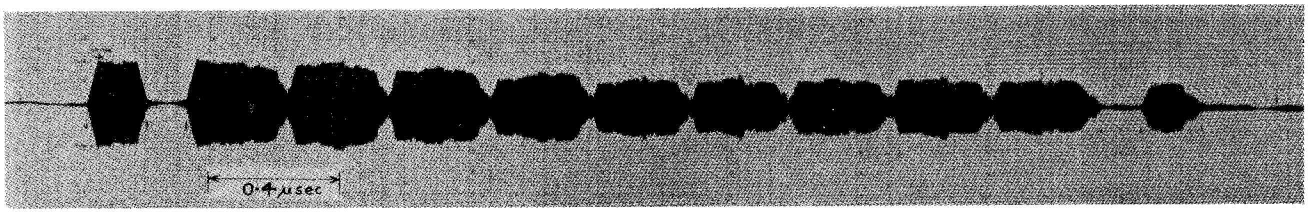

Fig.5 Transient response of 400 MHz delay-line with the two transducers having 10 and 2 rungs

At present the most stable oscillators are made on quartz by evaporation of approximately 1000 Å of aluminium followed by photolithographic pattern definition. Reproducibility depends on carefully controlling the metal thickness and mark/space ratio. Using a thinned transducer structure also aids reproducibility. A few faults have insignificant effect.

For an ST cut of quartz, with propagation in the X-direction a typical stability is 40 ppm for an operating temperature range of -10 to 60°C. To improve stability at AT cut slice can be temperature controlled and Figure 6 shows a measured characteristic of frequency against surface temperature for a cut of 35° 06'. The temperature needs only to be controlled to ± 5°C at the peak of the parabolic characteristic to achieve a stability of 1 ppm for the quartz. Amplifier phase shift will then tend to dominate; e.g. for a Mullard OM 337 amplifier the phase shift is -7° for 0 to 60°C resulting in 20 ppm frequency change with a 1000 λ delay line. Overall stability of approximately 5 ppm can be achieved with the quartz temperature controlled and with the amplifier phase compensated. This is comparable with uncontrolled bulk crystal oscillators at HF. Browning and Lewis[3] have demonstrated compensation of a delay-line by a composite delay-line structure giving ± 15 ppm from -40 to +100°C.

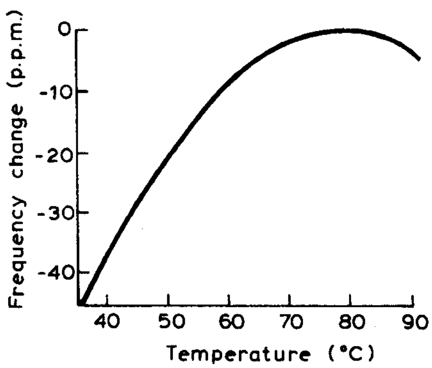

Fig. 6 Frequency change v temperature AT cut quartz (35° 06')

Frequency setting and tuning

Provided the filter response encompasses the required frequency, accurate frequency setting can be achieved by a combination of:

a) π phase change by reversing connections to one transducer
b) external transmission lines ≤ λ/4
c) trimming capacitors in external circuit.

Frequency setting accuracy has been achieved in the laboratory to ± 3 ppm.

Frequency modulation

The trimming capacitor can be a varactor and a phase shift of 40° can be obtained from a single varactor with resonanting inductor to restrict the mismatch to < 2:1. This gives a total deviation of $f_o/10\,n$. This range can be doubled by a network with two or more varactors.

The rate at which the frequency can be changed by a voltage step is dependent on the delay (τ) and a new frequency can be established for the same mode in < 3τ For square wave modulation therefore 1 cycle takes 6τ. Approximately 10τ is required for sinusoidal modulation according to Lewis[1].

Acknowledgement

The design of delay-lines, the transient response measurements and the derivation of the noise equations were performed by colleagues R Stevens and R N Bates.

The accurately reproduced SAW delay-lines have been made by P Mayor of the Central Materials Laboratory, Mullard Mitcham, Surrey.

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