Conjugate Regenerative Dividers

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***Abstract*—We discuss a novel design of a self-starting regenerative divider that permits division by 3, 4, 5, 6 ... instead of the usual 2. This is accomplished by having the loop oscillate simultaneously at two harmonically related conjugate frequencies, e.g., at $\nu/4$ and $3\nu/4$. A prototype of the divide-by-four circuit has been constructed for an input frequency of 400 MHz. This divider exhibits very low phase noise, £ (1 kHz) = −162 dBc/Hz and £ (100 kHz) = −170 dBc/Hz, which is approximately 9 dB lower than that of its constituent parts. Simple modifications of the feedback loop of this circuit enabled it to divide by 3, 5, and 8. Operation at higher division ratios appears feasible under certain conditions.**

I. Introduction

Frequency division is an important aspect of frequency synthesis schemes and has been applied extensively. In particular, regenerative dividers first proposed by Miller [1] have attracted considerable attention, mainly because they produce a clean sinusoidal output waveform and can be used at arbitrarily high frequencies. Several design aspects of regenerative divider circuits have been studied in recent years—primarily, their theory of operation [1]–[3] and their low phase-noise performance [4]–[7]. Regenerative dividers have successful application in low-noise microwave frequency synthesizer applications [7], [8]. Miller [1] had originally conceived the idea of a general division by N ($N \geq 2$), but most regenerative dividers have had divide-by-two configurations. To obtain greater division ratios, regenerative dividers have been cascaded, thus increasing the amount of hardware [9]. Alternately, it has been possible to achieve division ratios by inserting multipliers within the loop or by driving the mixer into hard saturation, which generates harmonics. Such highly nonlinear dividers are not always self-starting.

In the present study, we have attempted to overcome the above complexities by generalizing the regenerative divider configuration to permit division by 2, 3, 4, 5, 6, etc. A distinct difference in our approach compared to that of Miller is that the loop supports simultaneous oscillation at two different frequencies. This removes the necessity of using nonlinear elements (e.g., frequency multipliers) within the feedback loop to obtain integer frequency division higher than two. The linear nature of this loop makes it possible for the divider to be self starting.

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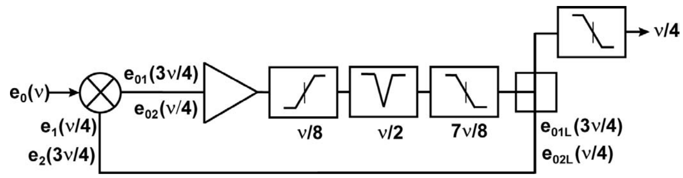

Fig. 1. Schematic of a divide-by-four regenerative divider.

A very simple theory has been worked out for the specific case of division by four, giving the conditions under which such a divider would operate and the phase noise that would be expected due to noise in the constituent parts. However, the methodology is general enough to be extended to other division ratios. A prototype divide-by-four divider has been fabricated with an input frequency of 400 MHz, primarily motivated by a plan to replace the corresponding digital divide-by-four divider in an existing Cs synthesizer [8]. Phase noise measurements carried out on the prototype show reasonably good agreement with expectations. We also show that, by appropriately adjusting the frequency response of the feedback loop of the divider, it is possible to obtain divisions by 3, 5, and 8. The extension to division by 10 is more difficult, but possible. Depending on the components chosen, it is possible to obtain a comb of harmonically related output frequencies, for example, $\nu/5$ and $2\nu/5$, $3\nu/5$, and $4\nu/5$.

II. Operation of Regenerative Divide-by-Four

Fig. 1 shows the schematic of our regenerative divide-by-four circuit. An examination reveals that it is essentially a conventional divide-by-two circuit, except for the transfer function of the feedback loop. Unlike the loop filter of the conventional divide-by-two, which consists only of a low-pass (or a band-pass) filter at $\nu/2$, we have a notch filter at $\nu/2$, a low-pass filter at about $7\nu/8$, and a high-pass filter at about $\nu/8$, where ν is the carrier frequency of the input signal to the divider. These filters yield a transfer function of the feedback loop with broad gain peaks around $\nu/4$ and its conjugate at $3\nu/4$. An initial filtered noise signal e_1 at a frequency near $\nu/4$ exists at one input of the mixer. This mixes with the input signal e_0 at frequency ν to produce the output e_2 at $3\nu/4$. The signal e_2 is amplified and propagates around the loop, because the loop transfer function also has a peak at this frequency causing it also to appear at the input of the mixer. It can then mix with the input e_0 to produce the output at $\nu/4$, which in turn propagates around the loop and, given the right phase conditions, reinforces e_1. Thus, in equilibrium we can have a situation where two signals at $\nu/4$ and $3\nu/4$ propagate around the loop and sustain each other. Either signal can be extracted using a power splitter as shown or directional coupler inserted into the loop.

The conditions under which the regenerative loop will function are as follows. Assume that the signals at the RF port of the mixer are the input e_0 at frequency ν and those at the LO port are e_1 and e_2 at frequencies $\nu/4$ and $3\nu/4$, respectively. We can write these signals as

$$e_0 = A\cos(2\pi\nu t) \tag{1}$$
$$e_1 = B\cos(2\pi(\nu/4)t + \theta_1) \tag{2}$$
$$e_2 = C\cos(2\pi(3\nu/4)t + \theta_2) \tag{3}$$

The amplitude terms B and C may be very small initially. At the output of the mixer we obtain the following outputs as we ignore the signals at the sum frequencies which are not supported in the loop.

$$e_{01} = K_1 AB\cos(2\pi(3\nu/4)t - \theta_1) \tag{4}$$
$$e_{02} = K_2 AC\cos(2\pi(\nu/4)t - \theta_2) \tag{5}$$

where K_1 and K_2 are the mixer conversion losses. Let us assume that the loop transfer function has the general form $G_1\angle\varphi_1$ and $G_2\angle\varphi_2$ at frequencies $\nu/4$ and $3\nu/4$, respectively. At the output of the loop filter and amplifier, the resultant signals are given by

$$e_{01L} = G_2K_1AB\cos(2\pi(3\nu/4)t - \theta_1 + \varphi_2) \tag{6}$$
$$e_{02L} = G_1K_2AC\cos(2\pi(\nu/4)t - \theta_2 + \varphi_1) \tag{7}$$

When we close the loop, oscillation is supported with the conditions

$$e_{01L} = e_2 \tag{8}$$
$$e_{02L} = e_1 \tag{9}$$

Using (2), (3), (6), and (7) and equating amplitude and phase terms, we then get the conditions for sustained regeneration as

$$K_1K_2G_1G_2A^2 \geq 1 \tag{10}$$
$$\varphi_1 = \varphi_2 + 2\,n\,\pi \tag{11}$$

The loop starts to regenerate if the total gain given in (10) exceeds unity and nonzero values of B and C are obtained when the loop saturates. Under the condition that the two signals are precisely harmonically related to each other, or that we have synchronous operation, e_2 is the 3rd harmonic of e_1, which implies that $\theta_2 = 3.\ \theta_1$. Using (2), (3), (6), and (7) again we get the further conditions

$$\theta_1 = \varphi_1/4 \tag{12}$$
$$\theta_2 = 3\varphi_2/4 \tag{13}$$

To satisfy (12) and (13), n in (11) must be equal to zero. In other words, this would require that the loop be nondispersive and have a short transit time. Note that no special starting conditions are required for initiating oscillations in the loop. Simultaneous oscillations at the two conjugate frequencies reinforce and eventually support each other.

We must, of course, realize that it is possible to have an asynchronous mode of operation [10], in which case the two frequencies propagating in the loop, rather than being precise harmonics of each other as above, just satisfy the condition that their sum is equal to ν. If (10) and (11) are satisfied, then the loop can regenerate with these two frequencies. There can be conditions when both synchronous and asynchronous modes coexist and compete with each other. This can happen particularly when the transit time through the loop is long.

It is clear that the theory of operation as given above is rather simplified and can at best be taken as a starting point in an attempt to develop a more complete theory. We venture to suggest some possible mechanism. Notice that the condition in (11) implies that the loop phase shifts at the two regenerating frequencies are matched to an infinite degree of exactness. This cannot normally be the case. However, we note that in order to stabilize (10) the conjugate amplitudes B and C usually reach near saturation levels under which condition there is a slight dependence of loop phase shifts with signal amplitude for each frequency. It is possible that initially the oscillations build up in an asynchronous way in which (11) is satisfied only approximately. However, after the amplitudes B and C have built up enough, to be near saturation, the conjugate signals probably fall into a process of self synchronization by appropriately adjusting their amplitudes so that (11) is satisfied exactly.

An important consequence of (12) is that, if there are any phase fluctuations in the loop due to noise in the components, their effect is reduced by a factor of four at the output. Thus, the phase-noise power, which is proportional to the square of the phase fluctuations, can be expressed for the ideal divide-by-four circuit as

$$S_\varphi^{\text{Divider}}(f) = \frac{1}{16}\left[S_\varphi^{300\text{ MHz}}(f) + S_\varphi^{100\text{ MHz}}(f)\right] \tag{14a}$$

In the case here the PM noise components of the feedback network at 100 MHz and 300 MHz are closely matched. For simplicity we will assume that they are equal to $S_\varphi^{100\text{ MHz}}(f)$, in which case we can simplify (14) to the following:

$$S_\varphi^{\text{Divider}}(f) = \frac{1}{8}\left[S_\varphi^{100\text{ MHz}}(f)\right] = S_\varphi^{100\text{ MHz}}(f) - 9\ dB \tag{14b}$$

For comparison, note that the PM noise of the conjugate divider is 4 dB less than that of a 400 MHz divide-by-two circuit followed by a 200 MHz divide-by-two circuit. Using the same components, two dividers in cascade yield

$$\begin{aligned} S_\varphi^{\text{Divider}}(f) &= \left(\frac{1}{16} + \frac{1}{4}\right) S_\varphi^{100\text{ MHz}}(f) \\ &= S_\varphi^{100\text{ MHz}}(f) - 5\ dB \end{aligned} \tag{15}$$

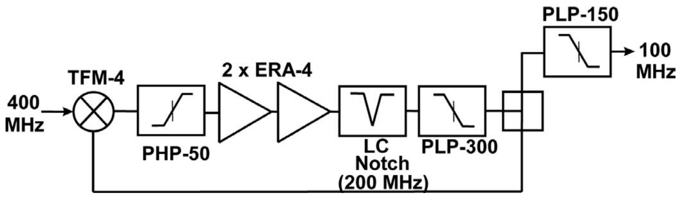

Fig. 2. Parts used in the prototype 400 MHz divide-by-four regenerative divider.

In practice it has been shown by Rubiola *et al.* [5] that the mixer is a complex device whose phase gain can vary considerably by the phase shift in the loop, which can cause the noise reduction shown in (14) to be worse under less than ideal conditions. Thus, one must fine trim the loop's phase delays to get the phase noise reduction close to that given by (14), perhaps at the expense of slightly lower output power.

Finally, note that the general conditions of synchronous operation that have been laid out above should be generally valid for other pairs of harmonically related conjugate frequencies such as $\nu/3 - 2\nu/3$ or $\nu/5 - 4\nu/5$, etc. Thus, given the right shape of the feedback-loop's transfer function and provided that the phase conditions are met, one can obtain regenerative division by 3, 5, 6, 7, 8, etc., without requiring nonlinearity in the loop.

III. Design of a Prototype Divide-by-Four

Fig. 2 shows the schematic of the prototype regenerative divide-by-four circuit designed to operate at an input frequency of 400 MHz. We used a mixer, low- and high-pass filters, a power splitter, all in modular versions, and two low noise amplifier stages.[1] The notch filter at 200 MHz consisted of a chip inductor of 10 nH in series with a chip capacitor of about 40 pF to ground. This produces a sufficiently deep notch that the divide-by-two mode is highly suppressed. The amplitude of transfer function of the feedback loop, shown in Fig. 3, clearly shows the two broad peaks around 100 MHz and 300 MHz. To close the loop from the output of the power splitter to the LO port of the mixer, we used a piece of 50 ohm 0.085″ coaxial cable. To get proper operation of the divider, the cable length had to be very carefully adjusted. Fig. 4 shows the output on a spectrum analyzer of the prototype divide-by-four circuit of Fig. 2. The input frequency to the circuit was 400 MHz and had a level between +5 and +10 dBm. The low-pass filter at 150 MHz was bypassed for the output shown in Fig. 4 to illustrate how the 300 MHz output can be extracted if desired. Division by $^3/_4$ is an additional by-product of the circuit.

[1]All parts used were modular units from Minicircuits as indicated in Fig. 2. The amplifiers were constructed out of ERA-4s, also from Minicircuits. This, however, does not constitute an endorsement of Minicircuits parts as being the best or the only ones suitable for this application. They were used to make the prototype due to their ready availability in our laboratory.

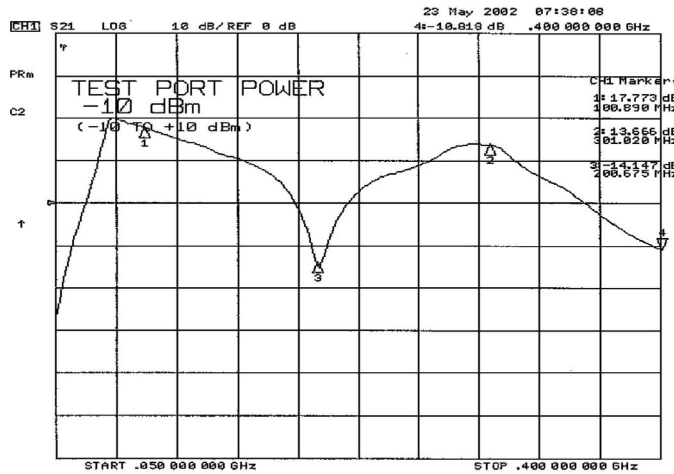

Fig. 3. Gain of the transfer function of the feedback loop.

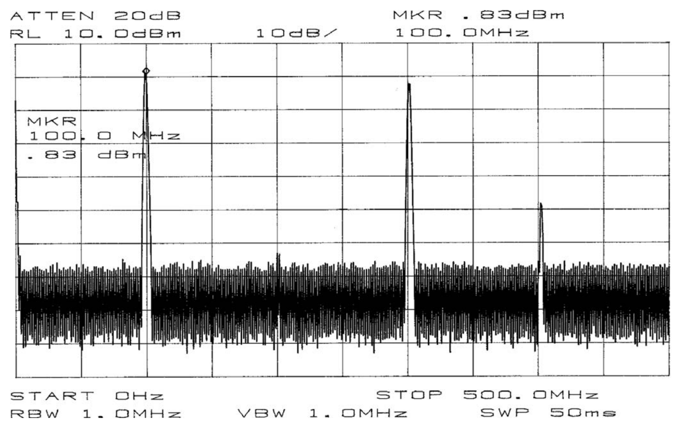

Fig. 4. Output of the regenerative divide-by-four circuit.

For a certain length of the feedback loop cable, the synchronous divide-by-four operation was found to take place over a variation of 400 MHz ± 10 MHz in the input frequency. Beyond this range the asynchronous modes begin to appear with the synchronous mode and the output starts to look like that shown in Fig. 5. To increase the synchronous operation bandwidth, the loop delay must be made as short as possible, with lower Q filters to reduce dispersion effects. One may attempt to increase the operational bandwidth by making the amplifier, rather than the mixer, the saturable element in the loop, as suggested by [10] in the context of divide-by-two circuits.

IV. Measurements of Phase Noise

Phase noise measurements were made on the prototype divide-by-four circuit using a cross correlation measurement setup [11]. The signal source was a low-noise 100 MHz quartz oscillator that was multiplied to 400 MHz using ultra-low-noise multipliers having a noise floor of −172 dBc/Hz. In the first part of the experiment, the noise of the entire feedback chain, comprising the amplifiers and

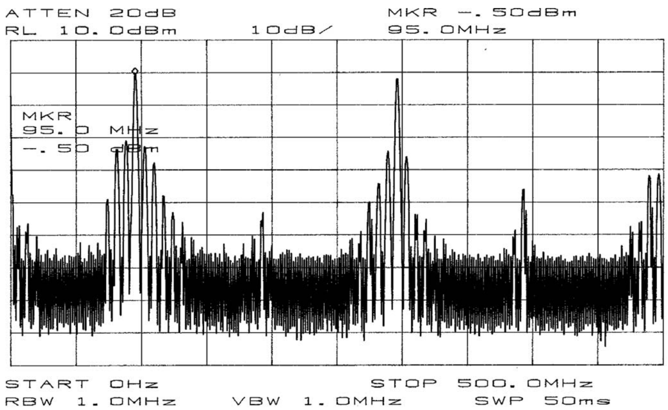

Fig. 5. Asynchronous operation of the divide-by-four circuit.

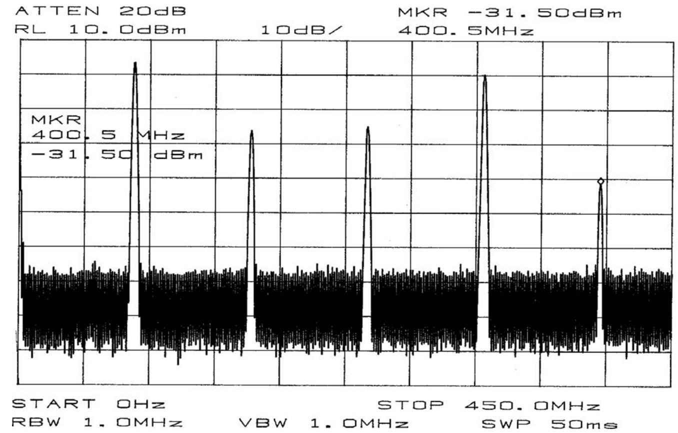

Fig. 7. Regenerative divide-by-five operation showing dominant outputs at $\nu/5$ and $4\nu/5$. Outputs are also present over a comb of frequencies including $2\nu/5$ and $3\nu/5$.

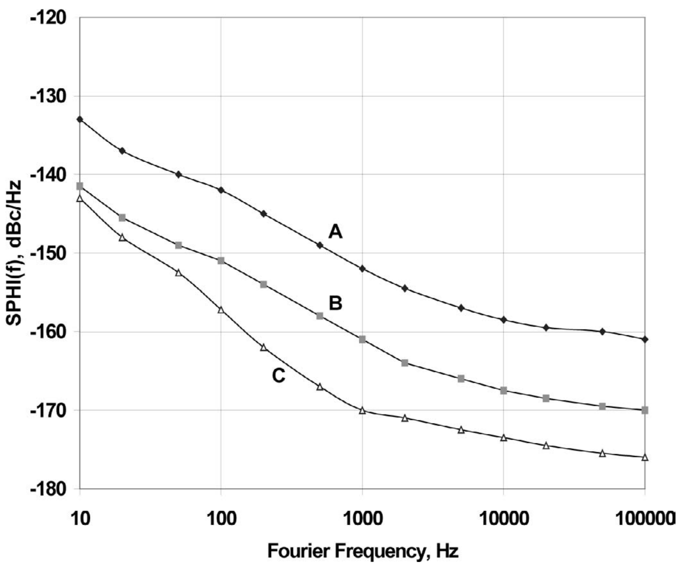

Fig. 6. Phase noise measurements of the divide-by-four circuit. Trace A shows values of the phase noise at 100 MHz of the feedback chain comprised of the amplifier and filters in open loop; Trace B is the phase noise of the divide-by-four circuit with output at 100 MHz, and Trace C is the noise floor of the measurement setup.

filters, was measured at 100 MHz. This is shown as Trace A in Fig. 6, where $\mathcal{L}(100 \text{ kHz})$ is within 2 dB of that expected from the input power and noise figure of the amplifier. Then the feedback loop was closed and phase noise of the divider output was made with input frequency of 400 MHz. This is shown as Trace B in Fig. 6. The loop phase delay had to be carefully adjusted to get the lowest noise values. Between the best and the worst performances there could be a degradation of the noise by about 6 dB. This is in agreement with the work of Rubiola [5]. The best noise values for the divider were $\mathcal{L}(1\,\text{kHz}) = -162\,\text{dBc/Hz}$ and $\mathcal{L}(100\,\text{kHz}) = -170\,\text{dBc/Hz}$. We observe that the values of Trace B are lower than those of Trace A by about 9 dB for all values of Fourier frequencies. This is in good agreement with the expected reduction of 9 dB in (14).

V. Division by N

Although the discussion in Section II focused on a division-by-four by considering a $\nu/4 - 3\nu/4$ conjugate pair, the technique can be generalized to pair $\nu/n - (n-1)\nu/n$. Given the appropriate loop-filter transfer function, other conjugate pairs such as—$\nu/3 - 2\nu/3$ or $\nu/5 - 4\nu/5$, or even $\nu/10 - 9\nu/10$, could also work in the synchronous mode. Indeed, by making simple modifications of the transfer function of the feedback loop in our prototype divide-by-four circuit in the form of different values of the low- and high-pass filter cutoffs and adjusting the phase delay we could operate the circuit as divide by 3, 5, 8, etc. The typical spectrum analyzer output for the case of division-by-five is shown in Fig. 7. In this case the most dominant outputs are at $\nu/5$ and $4\nu/5$, but other harmonics at $2\nu/5$ and $3\nu/5$ are also present. Likewise, for the case of division-by-eight we see a whole comb of outputs $n\nu/8$, $n = 1$ to 7. Practically speaking, the operational bandwidth of the loop decreases with increasing division ratio N.

VI. Parallel Configuration for Conjugate Operation

The operation of a conjugate-pair regenerative divider obtained using the notch filter at the half frequency $\nu/2$, as illustrated in Fig. 3, produces a filter transfer function that has two broad peaks symmetrically around $\nu/2$. This can then allow operations of conjugate frequency pairs of $\nu/3 - 2\nu/3$ or $\nu/4 - 3\nu/4$ and so on. For higher order division we get a complete comb of outputs $n\nu/N$ (except $\nu/2$). Conjugate regeneration can also be supported by an alternate form of feedback loop as shown in Fig. 8. In this configuration, the output of the mixer is split into two equal parts after amplification. Each of these two parts of the amplified outputs is passed through band-pass filters that are centered at the two conjugate frequencies and then are recombined again to be looped back to the mixer RF

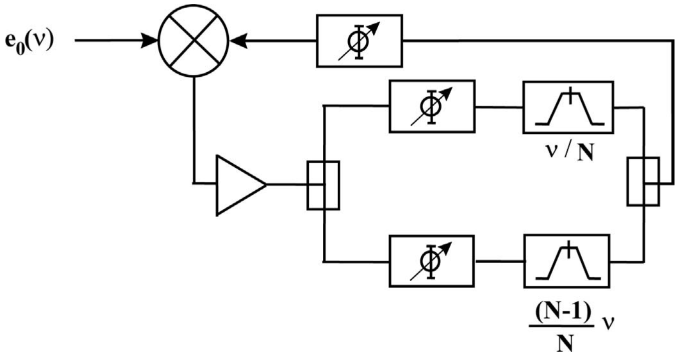

Fig. 8. Parallel filter configuration for regenerative divider.

port. Each filter arm also has a phase shifter to adjust the phase shift appropriately so that the oscillation condition is satisfied.

There are two main advantages of this parallel band-pass filter operation. First, one can make the pass band of the filters narrow enough that only one pair of conjugate frequencies, rather than the entire comb, propagates around the loop for a high order division. For instance, for division by 3/8 one can have band-pass filters at $3\nu/8$ and $5\nu/8$ so that only these two frequencies are able to regenerate. Second, two amplifiers can be used when the frequency of operation is so high that it is difficult to obtain amplifiers with sufficient bandwidth to span both conjugate frequencies. In such a situation, one can modify the configuration in Fig. 8 by removing the common amplifier after the mixer and introducing separate amplifiers preceding each of the two band-pass filters. Unlike amplifiers, the mixers are capable of operation over a much wider frequency band. Third, one can adjust the phase shifts in the two loops independently to obtain optimum operation of both loops.

Preliminary results on a parallel filter arrangement yields a PM noise floor similar to that obtained from the series filter of Fig. 3. The alignment of the divider of Fig. 8 is, however, much easier than for the divider of Fig. 3.

VII. Conclusion

We have shown that a modification of the feedback loop of a regenerative divide-by-two circuit can work as a divide-by-four. A simple theory of the condition of stable operation of the divide-by-four circuit has been presented. A prototype regenerative divider from 400 MHz to 100 MHz has been constructed and found to work reliably over a band of 20 MHz around the input frequency. Beyond this band, there are asynchronous and synchronous modes that inhibit stable operation. Preliminary measurements indicate that the divide-by-four circuit has a very low phase noise, $\mathcal{L}(1\text{ kHz}) = -162$ dBc/Hz and $\mathcal{L}(100\text{ kHz}) = -170$ dBc/Hz. These values are about 9 dB less than the phase noise of the components constituting the feedback loop.

It has been shown that by modifying the feedback loop transfer function it is possible to operate the divider as divide-by-3, -5, -8, etc. In fact, for the higher division ratios the output is actually a comb of outputs $n\nu/N$, $n = 1, 2, \ldots, N-1$. We have also shown that an alternate form of the feedback loop that incorporates two band-pass filters in a parallel configuration is also able to produce conjugate regeneration. This configuration is easier to tune and would be particularly useful to produce a specific subharmonic frequency, rather than a whole comb of subharmonics. Using parallel amplifiers and filters, operation of dividers is possible over large division ratios and at very high microwave frequencies.

It must be stated finally that our understanding of the theory of operation of the divider is very preliminary and will evidently require a more detailed analysis.

Acknowledgments

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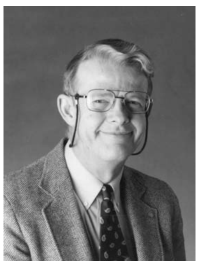

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From 1970 to 1973, he was a Postdoctoral Fellow at the Joint Institute for Laboratory Astrophysics in Boulder, CO. This work focused on developing techniques for long-term storage and nondestructive detection of fragile atomic ions stored in Penning traps for low energy collision studies. Since 1973, he has been a staff member of the Time and Frequency Division of the National Institute of Standards and Technology, formerly the National Bureau of Standards in Boulder. He is presently Leader of the Phase Noise Measurement Group and is engaged in research and development of ultra-stable clocks, crystal-controlled oscillators with improved short- and long-term stability, low-noise microwave oscillators, frequency synthesis from RF to infrared, low-noise frequency measurement systems, and accurate phase and amplitude noise metrology. He has published more than 150 scientific papers and articles. He holds five patents for inventions in the fields of frequency standards and metrology.

He received the 1995 European "Time and Frequency" Award from the Societe Francaise des Microtechniques et de Chromometric for "outstanding work in the ion storage physics, design and development of passive hydrogen masers, measurements of phase noise in passive resonators, very low noise electronics and phase noise metrology," He is the recipient of the 1995 IEEE Rabi Award for "major contributions to the characterization of noise and other instabilities of local oscillators and their effects on atomic frequency standards" and the 1999 Edward Bennet Rosa Award for "leadership in development and transfer to industry of state-of-the-art standards and methods for measuring spectral purity in electronic systems," He has also received three silver medals from the US Department of Commerce for fundamental advances in high resolution spectroscopy and frequency standards, the development of passive hydrogen masers and the development and application of state-of-the-art standards and methods for spectral purity measurements in electronic systems. Dr. Walls is a Fellow of the American Physical Society, a Senior Member of the IEEE, a member of the Technical Program Committee of the IEEE Frequency Control Symposium, and a member of the Scientific Committee of the European Time and Frequency Forum.