TABLE I
PHASE ANGLES ψ AND THE MAXIMUM OF ϕ_1 AND ϕ_2 AT f_1 AS A FUNCTION OF n AND f_2/f_1, THE RATIO OF STOP-TO-START FREQUENCY. THE MINIMUM EFFECTIVE PHASE SHIFT WHEN USING TWO LINES IS THE SMALLER OF ψ OR $\max(\phi_{1/f1}, \phi_{2f1})$. THE STAIR-STEP LINE INDICATES THE VALUES OF n AND f_2/f_1 WHERE $\psi = \max(\phi_{1/f1}, \phi_{2f1})$.

n =	0	1	2	3	4	5	6	7
ψ =		60	36	26	20	16	14	12
f2/f1	Max(φ1f1, φ2f1)							
1	90	90	90	90	90	90	90	90
2	60	60	60	60	60	60	60	60
3	45	90	90	45	45	90	90	45
4	36	72	72	72	36	36	72	72
5	30	60	90	90	60	30	30	60
6	26	51	77	77	77	51	26	26
7	23	45	68	90	90	68	45	23
8	20	40	60	80	80	80	60	40
9	18	36	54	72	90	90	72	54
10	16	33	49	65	82	82	72	65
11	15	30	45	60	75	90	90	75
12	14	28	42	55	69	83	83	83
13	13	26	39	51	64	77	90	90
14	12	24	36	48	60	72	84	84
15	11	23	34	45	56	68	79	90
16	11	21	32	42	53	64	74	85
17	10	20	30	40	50	60	70	80
18	9	19	28	38	47	57	66	76
19	9	18	27	36	45	54	63	72
20	9	17	26	34	43	51	60	69
22	8	16	23	31	39	47	55	63
24	7	14	22	29	36	43	50	58
26	7	13	20	27	33	40	47	53
28	6	12	19	25	31	37	43	50
30	6	12	17	23	29	35	41	46
32	5	11	16	22	27	33	38	44
34	5	10	15	21	26	31	36	41
36	5	10	15	19	24	29	34	39
38	5	9	14	18	23	28	32	37
40	4	9	13	18	22	26	31	35
42	4	8	13	17	21	25	29	33
44	4	8	12	16	20	24	28	32
46	4	8	11	15	19	23	27	31
48	4	7	11	15	18	22	26	29
50	4	7	11	14	18	21	25	28
55	3	6	10	13	16	19	23	26
60	3	6	9	12	15	18	21	24
65	3	5	8	11	14	16	19	22
70	3	5	8	10	13	15	18	20
75	2	5	7	9	12	14	17	19
80	2	4	7	9	11	13	16	18
85	2	4	6	9	10	13	15	17
90	2	4	6	8	10	12	14	16
95	2	4	6	8	9	11	13	15
100	2	4	5	7	9	11	12	14

values of f_2/f_1 and n where $\psi = \phi_{2f1}$. For example, when $f_2/f_1 = 65$ and $n = 5$, $\psi = \phi_{2f1} = 16°$. Any other value of n would give either ψ or ϕ_{2f1} smaller than 16°, indicating that $n = 5$ is the best choice at $f_2/f_1 = 65$. Experience on a dual six-port ANA at NBS indicates that it is probably not practical to let the minimum effective phase shift through the line fall below about 16° when calibrating the network analyzer.

The $n = 0$ column in Table I can be used to find the value of ϕ at f_1 when using a single line.

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Optical Injection Locking of BARITT Oscillators

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Abstract —**Optical injection locking of BARITT oscillators is investigated. Preliminary experimental results are presented for the first time. A simple first-order locking theory gives reasonable agreement with measurements.**

In modern high-performance radar systems, it is advantageous to use many low-power transmitters in an electronically steerable phase-array configuration. All these low-power transmitters have to oscillate with the same frequency and a given phase relation using locking signals distributed to the individual oscillators. This may be achieved by optical injection locking if electrooptic microwave semiconductor devices—e.g., IMPATT's—are used. These optical locking signals can then be distributed by optical fibers with the advantage of low loss, negligible dispersion, and low weight as compared with conventional microwave transmission lines.

Forrest and Seeds [1] have shown that optical injection locking of IMPATT oscillators should be possible. A large-signal theory of an IMPATT diode under the influence of intensity modulated light has been developed and a locking bandwidth of about 0.5 percent at X-band has been predicted but experimental results are still lacking. Optical injection locking of bipolar transistor oscillators at 1.8 GHz has been realized by Yen and Barnoski [2]. Recently, Sallas and Forrest [3] have demonstrated optical injection locking of GaAs MESFET oscillators at 2.35 GHz. With an optical power of about 1 mW, a locking bandwidth of 0.2 percent has been achieved.

In the following, the optical locking behavior of UHF-MSM-BARITT oscillators is investigated. To determine the locking bandwidth, the simple lumped model of BARITT oscillators as shown in Fig. 1 with the small-signal admittance Y_D of the BARITT device, the load admittance Y_L, and the ac locking current source I_{Ph} is used. The hole- or electron-locking current I_{Ph} is generated by illuminating one of the Schottky contacts with intensity modulated laser light (see inset in Fig. 2). Using the Adler criterion [4], one obtains a linear dependence of $\Delta\omega$ on I_{Ph} according to

$$\Delta\omega = \frac{\omega_o}{Q_L} \frac{|I_{Ph}|}{(8G_L P_{HF})^{1/2}} \quad (1)$$

where ω_o is the oscillator frequency, Q_L the loaded Q factor of the oscillator, G_L the load admittance, and P_{HF} the microwave output power of the oscillator. Assuming optical generation of carriers within surface layers only, it is easy to show that the photocurrent is approximately given by [5]

$$|I_{Ph}| = \frac{q\eta P\lambda}{hc} \frac{\left[\sin^2(\omega_{Ph}\tau) + \{\cos(\omega_{Ph}\tau) - 1\}^2\right]^{1/2}}{\omega_{Ph}\tau} \quad (2)$$

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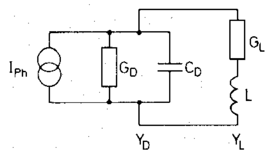

Fig. 1. Lumped model of BARITT oscillator used for locking analysis.

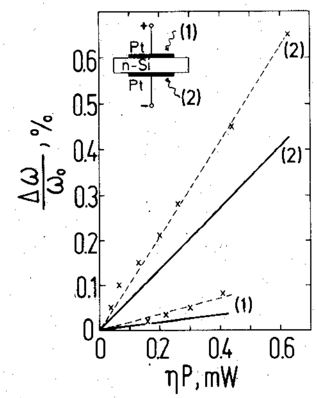

Fig. 2. Locking characteristics of BARITT oscillator. $\omega_o = 3.88 \times 10^9$ s^{-1}, $Q_L = 17$, $P_{HF} = 4.3$ mW, $G_L = 0.37$ mS. (1) Optical hole injection, $\tau_p = 1.45$ ns. (2) Optical electron injection, $\tau_n = 0.54$ ns. × × × × ×: measured; ——: calculated.

where ω_{Ph} denotes the modulation frequency of the optical signal, τ the transit time of the optically injected holes or electrons, respectively, P the total sideband power of the modulated optical signal, λ the vacuum wavelength of the light, and η a correction factor taking into account the quantum efficiency and the losses due to reflection at and absorption in the metallic contact. If neither the velocity of holes nor the velocity of electrons is saturated within the BARITT device, the transit time τ_n of electrons is shorter than the transit time τ_p of holes, hence the locking bandwidth in case of optical electron injection should be larger than in case of optical hole injection.

In the locking characteristics of Fig. 2, experimental and theoretical results are compared for optical hole and electron injection. As can be seen, the measured locking bandwidth increases linearly with optical power, and the locking bandwidth in case of electron injection is much larger than in the case of hole injection, as predicted by theory. Intensity modulated laser light ($\lambda = 633$ nm) was used as the optical locking signal. The loaded Q factor was measured with conventional electronic injection locking. The theoretical characteristics were calculated using the measured oscillator and circuit parameters, the numerically calculated small-signal admittance Y_D, and the transit times τ_p and τ_n.

As a result, the simple theory offers reasonable correlation as compared with the experimental results. However, the measured locking bandwidths are approximately 50 percent larger than the calculated bandwidths. This may be traced back to the fact that the simple theory does not allow for an optical modulation of the device admittance Y_D and its influence upon the locking characteristics. The locking bandwidth of about 0.6 percent as obtained with BARITT oscillators, is similar to the bandwidths predicted for IMPATT oscillators [1] and for transistor oscillators [2], [3]. Experimentally, it has been shown that optical injection locking of BARITT oscillators is possible. A locking bandwidth of 0.6 percent is obtained which may be viewed as a useful value. There is reasonable agreement between measurement and theory. In the higher microwave range, it is recommended to use light modulated by a subharmonic of the oscillator frequency as the optical injection signal because, at present, it might be difficult to modulate laser light using high microwave frequencies.

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Comments on "A Rigorous Technique for Measuring the Scattering Matrix of a Multiport Device with a Two-Port Network Analyzer"

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The recent article[1] by Tippet and Speciale uses the matrix formulation of the generalized scattering parameter renormalization transformation in the form

$$S' = (I-S)^{-1}(S-\Gamma)(I-S\Gamma)^{-1}(I-S). \qquad (1)$$

Here S is the $N \times N$ scattering matrix of an N port with port line impedances ζ, S' is the transformed scattering matrix when the port impedances are altered to Z, and Γ is the diagonal matrix of reflection coefficients of Z as seen from line impedances ζ, and I is the identity matrix.

Equation (1) can be simplified as follows:

$$S = (I-S)^{-1}S(I-S) \qquad (2)$$

$$S' - S = (I-S)^{-1}\left[(S-\Gamma)(I-S\Gamma)^{-1} - S\right](I-S). \qquad (3)$$

The bracketed term is

$$\begin{aligned}(S-\Gamma)(I-S\Gamma)^{-1} &- S(I-S\Gamma)(I-S\Gamma)^{-1}\\ &= [(S-\Gamma) - S(I-S\Gamma)](I-S\Gamma)^{-1}\\ &= -(I-S^2)\Gamma(I-S\Gamma)^{-1}.\end{aligned}$$

Note the cancellation of the individual S terms. Since $(I-S^2) = (I-S)(I+S)$, the prefactor in (3) also cancels, with the final result

$$S' = S - (I+S)\Gamma(I-S\Gamma)^{-1}(I-S). \qquad (4)$$

Equation 4 has reduced the number of matrix inversions needed from 2 to 1. Also, S' is now obtained by an additive correction to

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