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References

1 CHEN, B., and RAMER, O. G.: 'Diffraction-limited geodesic lens for integrated optic circuit', *IEEE J. Quantum Electron.*, 1979, **QE-15**, pp. 853–860
2 VAHEY, D. W., *et al.*: 'Effects of anisotropic and curvature losses on the operation of geodesic lenses in Ti:LiNbO$_3$ waveguides', *Appl. Opt.*, 1980, **19**, pp. 270–275
3 FEIT, M. D., and FLECK, J. A.: 'Light propagation in graded-index optical fibres', *ibid.*, 1978, **17**, pp. 3990–3998
4 YEH, C., *et al.*: 'Multimode inhomogeneous fiber couplers', *ibid.*, 1979, **18**, pp. 489–495
5 SOTTINI, S., *et al.*: 'General solution of the problem of perfect geodesic lenses for integrated optics', *J. Opt. Soc. Am.*, 1979, **69**, pp. 1248–1254

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NOVEL TWO-O.A. THREE-RESISTOR VARIABLE PHASE INVERTING AMPLIFIER

Indexing terms: Amplifiers, Active networks

A new active phase-compensated inverting amplifier is proposed. The amplifier circuit employs two o.a.s and three resistors and has an infinite input impedance. The proposed amplifier is also suitable for phase correction in two-integrator loop filters.

Introduction: Several methods have been presented for active phase compensation of the inverting amplifier.[1–3] In all these methods, the compensated amplifier has a finite input impedance.

This letter introduces a new active compensated inverting amplifier which employs two o.a.s and three resistors and has an infinite input impedance. The proposed amplifier has a larger gain-bandwidth product than the amplifier in Reference 1.

The new circuit is also suitable for realising a phase-lead inverting amplifier. Its application for phase correction in the Tow-Thomas biquad filter section[4,5] is discussed. In this respect, the proposed biquad filter uses three resistors less than that proposed by Reddy.[2]

Proposed inverting amplifier: The new inverting amplifier is shown in Fig. 1. Straightforward analysis of the circuit yields the following transfer function:

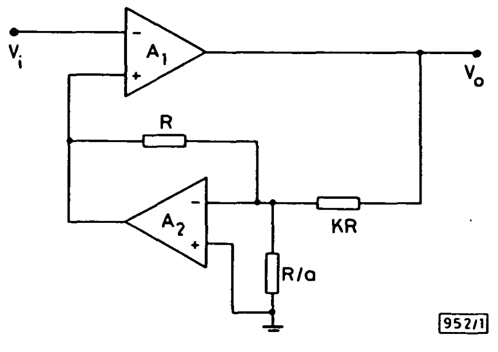

Fig. 1 *Proposed variable-phase inverting amplifier*

$$\frac{V_o}{V_i} = -K \frac{1 + \left[\frac{K(a+1)+1}{K}\right]\frac{1}{A_2}}{1 + K\frac{1}{A_1} + [K(a+1)+1]\frac{1}{A_1 A_2}} \quad (1)$$

Assume that matched o.a.s are used which are internally compensated to have a single-pole open-loop response with a unity-gain bandwidth ω_t. Thus the o.a. open-loop gain is approximately given by

$$A(s) \simeq \frac{\omega_t}{s} \quad (2)$$

Putting eqn. 2 in eqn. 1 gives

$$\frac{V_o}{V_i} = -K\varepsilon(s) \quad (3)$$

where

$$\varepsilon(s) = \frac{1 + \left[\frac{K(a+1)+1}{K}\right]\left(\frac{s}{\omega_t}\right)}{1 + K\left(\frac{s}{\omega_t}\right) + [K(a+1)+1]\left(\frac{s}{\omega_t}\right)^2} \quad (4)$$

$\varepsilon(s)$ is the remaining error function of the compensated circuit. In order to reduce the phase error to a negligible level, it is necessary that the coefficients of s in the numerator and denominator of $\varepsilon(s)$ be equal.[1] Thus the design value for a which provides phase compensation is given by

$$a = K - 1 - \frac{1}{K} \quad (5)$$

and the compensated error function reduces to

$$\varepsilon_c(s) = \frac{1 + s\tau_c}{1 + s\tau_c + s^2\tau_c^2} \quad (6)$$

where

$$\tau_c = K/\omega_t \quad (7)$$

The remaining phase and magnitude errors are given by

$$\left.\begin{aligned} \phi &= \arg \varepsilon_c(j\omega) \simeq -(\omega\tau_c)^3 \\ \gamma &= |\varepsilon_c(j\omega)| - 1 \simeq (\omega\tau_c)^2 \end{aligned}\right\} \quad (\omega\tau_c \ll 1) \quad (8)$$

Comparing the above errors with those obtained in Reference 1, it is clear that, for the same gain, the proposed circuit has smaller phase and magnitude errors than those obtained using the amplifier in Reference 1.

From eqn. 6, the 3 dB bandwidth of the proposed amplifier is given by

$$BW_c = \frac{1{\cdot}817}{K}\omega_t \quad (9)$$

For the inverting amplifier in Reference 1, and for the same d.c. gain, the bandwidth is:

$$BW_{S-I} = \frac{1{\cdot}817}{(K+1)}\omega_t \quad (10)$$

It is seen that the new amplifier has a larger gain-bandwidth product than the amplifier in Reference 1. On the other hand, it is seen from eqn. 5 that the proposed phase-compensated inverting amplifier is restricted to a d.c. gain of magnitude $\geq 1{\cdot}618$. This limitation does not exist in the Soliman-Ismail amplifier.[1] Also, for $K > 2{\cdot}414$, the latter circuit has a smaller resistance value spread.

Application in the Tow-Thomas biquad: The proposed circuit is suitable for use as a phase lead inverting amplifier. From eqns.

1 and 2, and for frequencies such that

$$\omega \ll \left[\frac{K}{K(a+1)+1}\right]\omega_t \tag{11}$$

eqn. 1 reduces to

$$\frac{V_o}{V_i} \simeq -K \Big/ \frac{\omega}{\omega_t}\left[a+1+\frac{1}{K}-K\right] \tag{12}$$

Phase correction in the Tow-Thomas biquad can be achieved if its inverter is replaced by the proposed phase-lead inverting amplifier, as shown in Fig. 2. To provide the amount of phase lead necessary for phase correction around the loop, a is taken as

$$a = K + 1 - \frac{1}{K} \tag{13}$$

In this case, the pole Q and the pole radian frequency of the inverter are given by:

$$\omega_a = \frac{\omega_t}{\sqrt{K(K+2)}} \qquad Q_a = \sqrt{\left(\frac{K+2}{K}\right)} \tag{14}$$

A figure of merit for the inverter is the $\omega_a Q_a$ product. A small value of K is desirable to obtain a large figure of merit. From the stability point of view, however, there is a lower limit on the value of K that can be used. The design equation for K is given next.

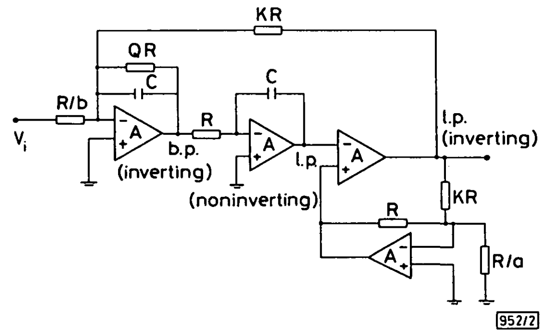

Fig. 2 *Improved Tow-Thomas biquad filter suitable for high Q and high frequency. Magnitude of gain at resonance at bandpass output = bQ. D.C. gains at the two lowpass outputs are b and −Kb, respectively*

Taking the second o.a. pole into consideration[6] and assuming that it occurs at a frequency ω_2 ($\omega_2 > \omega_t$), the open-loop gain A can be expressed as:

$$A(s) \simeq \frac{\omega_t}{s\left(1 + \dfrac{s}{\omega_2}\right)} \tag{15}$$

Putting eqns. 13, 15 into eqn. 1, it follows that a necessary condition for the stability of the phase-lead inverter is that

$$\omega_2 > \left[\frac{2}{K} - \frac{1}{2(K+2)}\right]\omega_t \tag{16}$$

As an example, taking $K = 1$ results in a figure of merit $= \omega_t$. In this case, $a = 1$ and the used o.a. must have $\omega_2 > 1{\cdot}83\omega_t$. On the other hand, taking $K = 2$ results in an unconditionally stable inverting amplifier, having a figure of merit $= 0{\cdot}5\omega_t$. In this case, $a = 2{\cdot}5$.

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References

1 SOLIMAN, A. M., and ISMAIL, M.: 'Active compensation of op-amps', *IEEE Trans.*, 1979, **CAS-26**, pp. 112-117
2 REDDY, M. A.: 'Operational amplifier circuits with variable phase shift and their application to high-*Q* active-*RC* filters and *RC*-oscillators', *ibid.*, 1976, **CAS-23**, pp. 384-389
3 NATARAJAN, S., and BHATTACHARYYA, B. B.: 'Design and some applications of extended bandwidth finite gain amplifiers', *J. Franklin Inst.*, 1978, **305**, pp. 321-341
4 TOW, J.: 'Active-*RC* filters—a state space realization', *Proc. IEEE*, 1968, **56**, pp. 1137-1139
5 THOMAS, L. C.: 'The biquad: part I—some practical design considerations; part II—a multipurpose active filtering system', *IEEE Trans.*, 1971, **CT-18**, pp. 350-361
6 MARTIN, K., and SEDRA, A. S.: 'On the stability of the phase lead integrator', *ibid.*, 1977, **CAS-24**, pp. 321-324

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CHARACTERISATION OF MULTIPLE-SCAN ELECTRON BEAM ANNEALING METHOD

Indexing terms: Charge carriers, Semiconductors

Beam power per unit area and exposure time are the predominant factors in defining implant anneal conditions for the multiple scan electron beam annealing technique. A theoretical analysis is presented which agrees with experimental results. Carrier concentration profiles confirm that the implant becomes electrically active without diffusion.

Dopants implanted into semiconductors may be activated during recrystallisation from the liquid state using pulsed lasers[1] or pulsed electron beams[2] or in the solid state using c.w. lasers,[3] scanned electron beams[4] or conventional furnaces. This letter reports the analysis of the multiple-scan e-beam annealing method, and presents experimental evidence that confirms the theoretical predictions.

Two distinct modes of scanning electron beam annealing have been developed.[5] In the single-scan method, shown in Fig. 1*a*, the beam activates the implant in the region under the beam. With sufficient overlap between adjacent scan lines, uniform annealing of large areas is obtained. The temperature rise under the beam depends on the ratio of beam power to radius, P/r. To stay in the region between incomplete activation and melting, this ratio must be controlled to $\pm 10\%$. Further, to ensure identical and reproducible heat flow conditions at each exposure point, the specimen must be provided with a heat sink.

In the multiple-scan method, the sample is exposed to multiple randomly interlaced raster scans of the beam. The method effectively gives uniform exposure over the scanned area, with a mean power density delivered to the specimen equal to the beam power divided by the scanned area. A minimum frame frequency of 4 Hz with line frequencies up to 50 kHz have been used to obtain uniformity of annealing. Neither the Gaussian spot size, beam voltage or current are critical parameters. Useful exposure times are in the region 0·1 to 10 s, in which time the specimen has been scanned many times. These specimens are kept deliberately in poor thermal contact with the carrier, and are approximately thermally isolated from it.

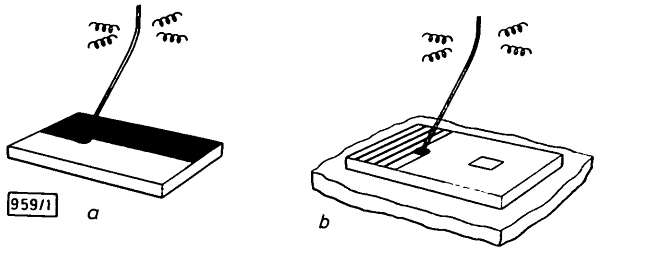

Fig. 1 *Scanning electron beam annealing methods*

a Multiple-scan method
No heat sink; effective power density = beam power/scanned area
b Single exposure method
Heat sink
Selected areas or single raster scan