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Simulation study of compact quantising circuits using multiple-resonant tunnelling transistors

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The authors have applied a simple modelling approach for multiple resonant tunnelling transistors (mRTTs) which includes four resonant tunnelling diodes (RTDs) within the transistor structure. Unique features of this model, corresponding to device features compatible for integrated circuits, allow for tuning and matching the devices for optimum circuit performance. Two circuits are presented for analogue to quaternary conversion with analysis of their transfer characteristics; this analysis is consistent with the simulation results and implies that circuits of physical devices may be successfully implemented.

Introduction: Interest in multiple-valued logic (MVL) systems has increased significantly over the past several decades, even as the digital, mostly binary, revolution has unfolded. To date, most MVL systems and circuits have been implemented using conventional MOS devices and technologies. Recent advantages in heterostructure fabrication techniques have increased the stability and performance of these circuits. Among these, the multiple resonant tunnelling transistor (mRTT) family of devices, so-called because mRTTs incorporate several resonant tunnelling diode (RTD) structures in one or more device junctions, has been used for various MVL applications. Analogue to quaternary converters (AQC) or four-level quantising circuits are particularly important because the quaternary (base four) system is the simplest and most feasible for short-term implementation and because compact analogue to MVL converters are fundamental blocks for most MVL systems. In this Letter, we present a simple model for four RTD devices incorporating four RTDs (Fig. 1a) and discuss the operation of two compact AQC circuits (Fig. 2a and Fig. 3a) using such devices. A brief discussion of our mRTT model is necessary in order to understand the unique features of the operation of these circuits. However, our emphasis here is on how each circuit capitalises on the natural quantising ability of the mRTT devices and on the ability to match or ‘tune’ devices for optimal AQC performance.

Device model: We model the nonlinear, RTD-like $I_{V_{ex}}$ characteristic using combinations of Gaussian and exponential functions similar to the model discussed in [3]. To model the $I$-$V$ characteristic of a multiple RTT (mRTT), we introduce a Gaussian term for each RTD in the base-emitter junction. The total term has his as having own amplitude ($A_{1}, A_{2}, ...$) and spaced at integral multiples of $V_{ex}$ in voltage. Although the Gaussian amplitudes are completely independent parameters, all Gaussian terms are assumed to have a common width $\sigma$. Additionally, we include a single exponential term with amplitude $A_{e}$ and an exponential scaling constant $\alpha$, to represent the thermionic emission across the device. The operation of each scale factor $A_{i}$. Consequently, our model for an mRTT with four RTDs in the base-emitter junction results in the expression of collector current $I_{C}$ against base-emitter voltage $V_{ex}$ shown in Fig. 1b and expressed in eqn. 1.

$$I_{C} = A_{B} \exp[(V_{BE} - V_{PK})^2/2\sigma^2] + A_{D_{2}} \exp[(V_{BE} - 2 \times V_{PK})^2/2\sigma^2] + A_{D_{3}} \exp[(V_{BE} - 3 \times V_{PK})^2/2\sigma^2] + A_{D_{4}} \exp[(V_{BE} - 4 \times V_{PK})^2/2\sigma^2] + A_{E} \exp[(V_{BE} - A_{pk} + V_{PK})/\alpha] \quad (1)$$

In eqn. 1, $V_{PK}, \sigma, A_{B}, A_{E}$, and $\alpha$ are constants which depend on the general shape of the $I_{C}$ against $V_{ex}$ characteristic of the specific device being modelled. For this study, we use fixed values of 0.5V, 0.18V, 0.24, 1.2 and 1.0 for $V_{PK}, \sigma, A_{B}, A_{E}$, and $\alpha$, respectively.

Circuits and simulation results: Although this mRTT model has several limitations as compared to more elaborate models, it yields simulation results similar to published results of other mRTT circuits [2]. Thus, this simple model has some validity and may serve as a tool for investigating other mRTT circuits. In our case, we are seeking to develop an AQC using as few devices as possible and having a transfer characteristic as close to the ideal as possible. The ideal AQC transfer curve should have four distinct flat states or steps, uniformly spaced with very sharp transitions between states, and resembling, overall, four steps of a staircase. Fig. 2a presents our first attempt at achieving this ideal. We now analyse the normalised, simulated transfer characteristic ($V_{out}/V_{PK}$ against $V_{in}/V_{PK}$) for this circuit (Fig. 2b).

The output of Fig. 2b is obtained when mRTT1 and mRTT2 are ‘matched’ and ‘tuned’. The devices are matched by forcing device parameters $A_{P1}, ..., A_{P4}$ and $A_{E}$ for mRTT1 and those for mRTT2 to be equal. Technologically speaking, this means that mRTT1 and mRTT2 are fabricated from the same material, a condition necessary for integrated circuits. The devices are tuned by adjusting device parameters so that the transfer characteristic is as close to ideal as possible. This transfer characteristic may be explained by assuming that the two collector currents are equal, as...
expressed in eqn. 2, and by noting the control voltages for each device, expressed in eqns. 3 and 4, for various ranges of $V_{in}/V_{pk}$:

$$I_{C1} \approx I_{C2} \quad (2)$$

$$V_{BE1} = V_{IN} - V_{OUT} \quad (3)$$

$$V_{BE2} = V_{IN} \quad (4)$$

Combining eqns. 3 and 4,

$$V_{OUT} = V_{BE2} - V_{BE1} \quad (5)$$

As $V_{in}/V_{pk}$ increases from 0 to 1, the collector current of each device increases; the operating point of both devices moves from point O through point A to point B of Fig. 1b. For these conditions, eqn. 2 requires that the controlling voltages, $V_{BE1}$ and $V_{BE2}$, are equal. Substituting into eqn. 5 yields $V_{OUT} = 0$. The non-zero behaviour of $V_{out}/V_{pk}$ in Fig. 2b for $0 < V_{in}/V_{pk} < 1$ is due to the non-linear input impedance of the mRTTs, which causes a significant deviation from eqn. 2 in this region.

$$V_{OUT}/V_{PK} \approx 0 \quad \text{for} \quad 0 < V_{IN}/V_{PK} < 1 \quad (6)$$

As $V_{in}/V_{pk}$ increases from 1 to 1.5, eqns. 1 and 4 force $I_{C2}$ to decrease; $I_{C1}$ must also decrease, by eqn. 2. Consequently, while the operating point of mRTT2 moves forward from point B to point C of Fig. 1b, the operating point of mRTT1 moves backward from point B to point A. Thus, $V_{BE2}$ decreases and $V_{BE1}$ increases, implying that $V_{out}/V_{pk}$ increases for $1 < V_{in}/V_{pk} < 1.5$.

Device matching and tuning yields very interesting $V_{OUT}$ behaviour for the next interval of interest, $1.5 < V_{in}/V_{ pk} < 2$. In this region, $I_{C2}$ increases by eqns. 1 and 4, so $I_{C1}$ also increases. Thus, the operating point of mRTT2 moves forward from point C to point D of Fig. 1b, while the operating point of mRTT1 moves forward from point A to point B. From Fig. 1b, the trajectories of these two operating points are very similar, a similarity which may be expressed by the following approximation:

$$V_{BE2} \approx V_{BE1} + C \quad \text{for} \quad 1.5 < V_{IN}/V_{PK} < 2 \quad (7)$$

where $C$ is some constant (about $V_{BE}$ from Fig. 1b). Substituting this information into eqn. 5 yields:

$$V_{OUT} \approx V_{PK} \quad \text{for} \quad 1.5 < V_{IN}/V_{PK} < 2 \quad (8)$$

That is, the matching of the shape of $I_{C}$ against $V_{BE}$ for the first and second current peaks (Fig. 1) leads to a 'plateau' in the transfer characteristic for $1.5 < V_{in}/V_{pk} < 2$. This conclusion is verified by the simulated output in Fig. 2b. Similar arguments show that matching the shapes of the first and third and of the first and fourth current peaks result in plateaus in the transfer characteristic:

$$V_{OUT}/V_{PK} \approx 2 \quad \text{for} \quad 2.5 < V_{IN}/V_{PK} < 3 \quad (9)$$

$$V_{OUT}/V_{PK} \approx 3 \quad \text{for} \quad 3.5 < V_{IN}/V_{PK} < 4 \quad (10)$$

Because the simulated transfer curve (Fig. 2b) verifies the relations in eqns. 6-10, this analysis adequately explains the operation of this circuit. This analysis is further validated by the fact that the 'best' AQC characteristics are obtained by tuning $A_{1} - A_{4}$ so that the heights of the current peaks are roughly equal.

Undesired features in the circuit of Fig. 2 include the relatively narrow plateaus (approximately 0.5° in $V_{BE}$) and the relatively sloped (but not steep) transitions. Both of these features may be significantly improved by simply adding a second stage, as shown in Fig. 3a.

The simulation results shown in Fig. 3b are obtained by tuning the model parameters $A_{1}, A_{2}, A_{3}, A_{4}, A_{5},$ and $A_{6}$. Optimal results are obtained when $A_{6}$, the device-area parameter, is matched for the devices within each stage. That is, $A_{j}$ of mRTT1 equals that of mRTT2, while $A_{j}$ of mRTT3 matches that of mRTT4. To support integration of the devices within the same substrate, the individual current peaks ($A_{1}, A_{2}, A_{3}, A_{4}$) are adjusted separately, but held constant for all devices. For example, $A_{1}(mRTT1) = A_{1}(mRTT2) = A_{1}(mRTT3) = A_{1}(mRTT4)$, but $A_{2}$ is not necessarily equal to $A_{2}$.

It may be interesting to note that the optimal set of device parameters for the dual-stage AQC (Fig. 3) is different to that for the single-stage AQC (Fig. 2). This is due to the non-linear input impedance (loading) included in each device model. Also of note is the impact of an individual current peak. For example, increasing $A_{3}$ increases the 'flatness' of the third plateau and the 'steepness' of the third transition, but decreases the flatness of the fourth plateau. Similarly, increasing the ratio of $A_{4}$ (mRTT1) to $A_{4}$ (mRTT3), that is, the ratio of the 'gain' of stage 1 to that of stage 2, decreases the flatness of all plateaus but increases the steepness of all transitions.

Summary and conclusions: Using a simple approach for modelling the $I_{C}-V_{BE}$ characteristic for mRTTs, we allow for adjusting device parameters consistent with technological features such as the device area ($A_{j}$) and thin-film thicknesses ($A_{1}, A_{2}, A_{3}, A_{4}$). We have presented two compact AQC circuits and an analysis of these circuits which is consistent with the obtained simulation results. Furthermore, since our analysis is based strongly on the match between the shapes of individual current peaks and not on the symmetry, asymmetry or absolute shapes of the current peaks, we conclude that there is a good possibility of obtaining the desired AQC transfer characteristics in circuits of actual mRTT devices.

Optimal focusing of scalar fields subject to arbitrary upper bounds

T. Isernia and G. Panariello

The authors present a new approach for determining the excitations of a given set of sources that will produce a maximum field in a given direction subject to arbitrary sidelobe bounds. The approach guarantees attainment of the globally optimal solution for a large class of pencil beam synthesis problems, including possible near field constraints.

Introduction: In the general case, power synthesis techniques are optimisation procedures, which, in order to achieve the design goals, rely either explicitly or implicitly on the minimisation of a proper function of the set of parameters specifying the antenna structure and excitations. Because of the inherent nonlinearity of the problem, such a function usually has many local minima which can 'trap' the algorithm. As a consequence, the designer could be led to the wrong conclusion, i.e. that the specifications cannot be met, and, even if the synthesis is successful, there is usually no way to judge if the design could be improved, (for instance, by using a smaller number of feeds, or a smaller antenna). Use of genetic algorithms [1] has recently been proposed in order to avoid the trapping problem. However, such 'global' optimisation approaches are extremely heavy from the computational point of view.

Assuming a given set of N sources, each radiating a known (scalar) field $\Psi_{i}(r)$ (i = 1, ..., N), the aim of this Letter is to show how, in a simple manner and with little computational effort, it is possible to find globally optimal solutions to the class of power pattern synthesis problems:

Find excitations $C_{j}$ (j = 1, ..., N) of the given sources such that: