A stepped-impedance true time delay line using GaAs MMIC technology

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Abstract: A new true time delay line (TTDL) using a stepped impedance (SI) structure is proposed for compact and wideband TTDLs in GaAs MMICs. An equivalent circuit model and a dispersion equation for the proposed SI-TTDL are also presented. Experimental verification and comparison with a conventional design are provided. The group delay of the proposed SI-TTDL is substantially increased up to approximately twice of a conventional microstrip transmission line in GaAs MMICs.

Keywords: MMIC, slow-wave, stepped impedance, true time delay

Classification: Microwave and millimeter-wave devices, circuits, and modules

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1 Introduction

A true-time-delay line (TTDL) is adopted in various microwave applications such as phased-array systems, synthetic aperture radars, delay-lock loops, and feed-forward amplifiers [1, 2, 3]. TTDLs are required to transfer the microwave signals with constant and large group delay over a wideband frequency range in a compact area. Different techniques are presented to realize TTDLs, namely using MEMS devices, optical networks, and left-handed metamaterials [4, 5, 6]. A MEMS-based TTDL can be implemented by particular process steps, thus having a limited amount of delay and increasing in manufacturing costs. An optical TTDL employs optical fibre cables with complicated transducers for the conversion of microwave signals into optical waves. The microstrip transmission line employing a composite right/left-handed metamaterial scheme has narrow bandwidth operation. Hence, the approaches have difficulty in the simultaneous imposition of multiple requirements.

In this letter, a stepped impedance TTDL (SI-TTDL) is proposed to achieve the large and constant group delay over a wideband frequency range. The proposed SI-TTDL is implemented by using a standard GaAs MMIC process, hence it can be easily integrated with other circuits. Compared to a conventional microstrip line, it is experimentally demonstrated that a compact size with a substantial increase in a time delay is achieved.

2 Design of stepped-impedance true time delay line

The proposed TTDL employs a stepped impedance structure to slow down a microwave signal. The proposed SI-TTDL consists of meandered and interdigitated microstrip transmission lines (TLs) on a GaAs substrate as shown in Fig. 1. The meandered TL is the inductive TL with a narrow width and bended shape, whereas the interdigitated TL is capacitively shorted to ground of the GaAs substrate. The inductive and capacitive TLs can be represented by the TLs having a high and low characteristic impedances (high- and low-Zo). The equivalent circuit model for the proposed SI-TTDL is presented using transmission line models as shown in Fig. 2. From the model, the dispersion equation for a phase constant and a group delay is derived in the following [7, 8]:

\[ \cos(\beta d) = \frac{(1 + K)^2}{4K} \cos(\beta_H d_H + \beta_L d_L) - \frac{(1 - K)^2}{4K} \cos(\beta_H d_H - \beta_L d_L), \]

\[ \tau_g = \frac{\partial \beta}{\partial \omega} \cdot d = \frac{d}{2\pi} \frac{\partial \beta}{\partial f}, \]

where, \( K = Z_{oH}/Z_{oL} \). The \( Z_{oH} \) and \( Z_{oL} \) are the characteristic impedances of the meandered and interdigitated TLs. \( \beta, \beta_H, \) and \( \beta_L \) are the phase constants of the SI-TTDL, the meandered TL and the interdigitated TL, respectively. \( d = d_H + d_L \), with \( d_H \) and \( d_L \) being the lengths of two meandered TLs and an interdigitated TL.
is the time delay of the SI-TTDL. Using the equations above, the slow-wave principle of the SI-TTDL can be explained.

### 3 Measurement results

The proposed SI-TTDL is fabricated using a commercial GaAs 0.25-μm pHEMT MMIC technology provided by WIN Semiconductors. The design parameters and the dimensions are shown in Fig. 1 and Table I, respectively. In Table I, the $Z_{olH}$ and $Z_{olL}$ are calculated using the electromagnetic simulation based on method of moments [9]. The scattering parameters are measured using a vector network analyzer and high-frequency GSG-type probes with 100-μm pitch. Fig. 3 depicts the photograph of SI-TTDL and measurements of slow-wave characteristics and scattering parameters.
In Fig. 3b, the slow-wave factor (SWF) and the characteristic impedance $Z_c$ of the SI-TTDL are extracted from the measurements of the S parameters [10]. Compared to the propagation constant $k_0$ of light in air, the SWF of the SI-TTDL is substantially increased up to 6.5. Moreover, the SWF variations with respect to the frequency is small so as to achieve the flat time delay over the wideband frequency range from 4 GHz to 20 GHz. The $Z_c$ of the SI-TTDL is approximately $47.5 \Omega$ which is compatible to 50-Ω RF and microwave systems. The $S_{21}$ and $S_{11}$ in the frequency of 20 GHz are $-0.2 \text{ dB}$ and $-23 \text{ dB}$, respectively.

In most TTDL applications, the characteristics of TTDLs is mainly expressed as a time delay (i.e., group delay). To verify the large time delay characteristics, the SI-TTDL with 7 cells and a microstrip TL are fabricated additionally as shown in Fig. 4. Their total lengths are the same as 2415 μm. Time delay characteristics is extracted from the measurements of S-parameters as shown in Fig. 5. The time delay of the SI-TTDL with 7 cells is approximately 63 ps while that of the

![Fig. 3. (a) Photograph of SI-TTDL in GaAS substrate, (b) slow-wave factor and characteristic impedance extracted from measurements, and (c) measurements of S-parameters.](image)

| Table I. Design parameters and dimensions for SI-TTDL in GaAs MMICs |
|-----------------|-----------------|-----------------|-----------------|
| Parameters      | Dimensions      | Parameters      | Dimensions (μm) |
| $d_{HI}$ (μm)   | 260             | $L_1$ (μm)     | 140             |
| $d_{Li}$ (μm)   | 85              | $L_2$ (μm)     | 80              |
| $w_{HI}$ (μm)   | 20              | $S_1$ (μm)     | 5               |
| $w_{LI}$ (μm)   | 5               | $S_2$ (μm)     | 5               |
| $Z_{oHI}$ (Ω)   | 68              | $Z_{oLI}$ (Ω)  | 33              |
microstrip TL is 28 ps. The difference in time delays of the SI-TTDL and the microstrip TL is approximately 35 ps in the frequency range from 4 GHz to 20 GHz. The time delay variations of the SI-TTDL is small over the wideband frequency range, thus achieving the flat time delay in wideband operation. The time delay of the SI-TTDL is more than twice as large as that of the microstrip TL in the same length. It is expected that the proposed SI-TTDL accomplishes the large time delay in the wideband frequency range within compact area.

Fig. 4. (a) Photograph of microstrip transmission line for a reference and (b) SI-TTDL for a delay line.

Fig. 5. Comparison of time delay characteristics extracted from measurements.

4 Conclusion

The novel slow-wave transmission line using stepped impedance technique is proposed for compact and wideband true time delay lines in GaAs MMICs. The proposed SI-TTDLs with 1 cell and 7 cells are fabricated and obtained the time delay characteristics through measurements. The slow-wave factor and characteristic impedance of the 1-cell SI-TTDL are 6.5 and 47.5 Ω, respectively, in the frequency range from 4 GHz to 20 GHz. Compared to the time delay of 28 ps for the conventional microstrip TL in the GaAs substrate, the time delay of the 7-cell
SI-TTDL is substantially increased up to 63 ps. The proposed SI-TTDL achieves the large and flat time delay over the wideband frequency range in the compact chip area.

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