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Multi-channel FSK Inter/Intra-chip Communication by Exploiting Field-confined Slow-wave Transmission Line

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Abstract— Using on-chip slow-wave transmission line (SW-TL) has paved a new way towards millimeter-wave (mm-wave) to terahertz (THz) low power and high speed inter-/intra-chip communications. This work presents an on-chip SW-TL featured by periodic comb-shape grooves with capability to strongly localize electric-field. A gradient groove structure is proposed to serve as the mode converter and performs the mode transformation between the quasi-TEM wave and the slow-wave with low return loss. Due to field confinement, when two SW-TL are only 2.4 μm apart, more than 19 dB crosstalk suppression is observed compared with two conventional TL with the same metal spacing. A dual-channel 160 GHz frequency-shift keying (FSK) transceiver is designed in 65 nm CMOS technology. The preliminary results show that by exploiting SW-TL as the silicon channel, the receiver can recover error-free 4 Gb/s dual-channel data, whereas the eye diagram of the transceiver using traditional transmission line (TL) is fully distorted. The transceiver consumes 36 mW DC power from a 1.2 V power supply.

Keywords—CMOS transceiver, terahertz, slow-wave, crosstalk, transmission line, inter-/intra chip communication

I. INTRODUCTION

Future Exascale computing require low power yet high speed chip-scale communication between microprocessor cores and memory. The data-rate is increasing for multi-Gigabit per second multi-channel OOK/FSK/BPSK data communication, and becomes a bottleneck at terahertz (THz) region between electronics and photonics [1–5]. The optical I/O [1] has power/cost overhead of O/E conversion and integration on silicon for short-distance communication, yet the electronic I/O [5] is constrained by huge metal loss and silicon channel crosstalk beyond GHz.

As the CMOS transistors are operating towards their maximum oscillation frequency $f_{\text{max}} \approx 200$ GHz [6], reducing metal radiation loss becomes increasingly important. The main loss of electronic signal from mm-wave to THz is the radiation loss in the form of thin-film metal skin and proximity effect. Traditional on-chip interconnect structures such as transmission line (TL) or microstrip line are vulnerable to lossy substrate and adjacent conductors, and thereby introducing electromagnetic (EM) crosstalk between silicon channels. Recent developments of slow-wave transmission line (SW-TL) have found extensive usage in THz region because of its ability to shrink the interconnect length through increasing the effective dielectric constant ϵ_{eff} [7–12]. By periodically putting isolating stubs beneath the conventional TL, ϵ_{eff} is boosted and thereby enhances the quality factor Q for signal transmission. However, all these approaches are limited to single-channel communication because channel crosstalk is

Fig. 1 Simulated (line) and modelled (dot) dispersion curves.

still dominant if two SW-TL are radically close, which are commonly observed in recent effort on inter-/intra chip communication.

This paper addresses the design of on-chip SW-TL suitable for multi-channel communication with channel crosstalk inherently suppressed. The SW-TL is featured by corrugating periodic grooves onto traditional TL. As shown in Fig. 1, by artificially designing the groove depth h , the proposed SW-TL exhibits a slow-wave characteristic whose dispersion curve can be easily manipulated. An FSK transceiver is designed as a vehicle to test this conjecture. The preliminary results demonstrates a crosstalk-immune 4 Gb/s dual-channel communication over the proposed 2 mm SW-TL channel with 2.4 μm channel spacing, validating the potential to replace the existing silicon channels.

II. SYSTEM ARCHITECTURE

Three mainstreams of modulation schemes, including OOK, FSK and BPSK, are preferred for short-range inter-/intra chip communications. OOK transceiver features the most direct implementation solution with the least circuit building block, but it must provide sufficient output power to satisfy link budget. This will render the system to be power hungry at THz since high power is normally required to compensate for process, voltage and temperature (PVT) variation. Compared to OOK, BPSK requires less signal-to-noise ratio (SNR) to achieve the same bit error rate (BER). Unfortunately, BPSK relies on coherent detection and thereby the use of frequency synthesizers, which are complex, power hungry, and sensitive to clock distribution path. Moreover, the power amplifier (PA) needs to operate in back-off region to satisfy linearity requirement, which further reduces the power efficiency.

Instead, FSK requires moderate circuit complexity and power. More importantly, it can tolerate large amplitude fluctuation, PVT variation, and also omits the need of

Fig. 2 Multi-channel FSK inter-/intra chip transceiver architecture and communication suffering from channel crosstalk.

Fig. 3 (a) Field-confined SW-TL, and (b) simulated E -field distribution of the SW-TL.

Fig. 4 Die photo of the field-confined SW-TL [3].

Fig. 5 Measured S11 (line) and S21 (dot) of the SW-TL.

frequency synthesizer. As such, FSK is considered in this work as shown in Fig. 2, where the transmitter is composed of an open-loop direct modulation of a voltage-controlled oscillator (VCO), and a PA, whereas the receiver contains a low-noise amplifier (LNA), a quadrature oscillator, two IQ mixers, and baseband limiting amplifiers. Eq. 1 below represents a continuous phase FSK signal whose phase change is related to the VCO center frequency [13]:

$$S_{FSK}(t) = A_0 \cos[\omega_0 t + D_f \int_{-\infty}^t m(\lambda) d\lambda] \quad (1)$$

where A_0 is the constant signal swing, ω_0 is the VCO center frequency, D_f is proportional to the maximum frequency offset from ω_0 , and $m(t)$ is the baseband signal. (1) reveals two advantages using FSK modulation: 1) the constant amplitude A_0 implies the use of PA operating in the

Fig. 6 (a) Die photo of the proposed dual-channel SW-TL [4], and (b) simulated E -field distribution in the xy -plane.

Fig. 7 Measured S11 (line) and far-end crosstalk (S41, dot) of the proposed dual-channel SW-TL (2.4 μ m channel spacing).

maximum power-added efficiency (PAE) region, and 2) since the recovered signal is immune to voltage clipping in the receiver chain, the receiver design can be much relaxed. Unfortunately, high frequency FSK I/O are vulnerable to channel crosstalk. A voltage perturbation coming from the aggressor channel fluctuates the amplitude A_0 , and also modulates the frequency offset. This will confuse the data recovery in receiver due to FM-AM or FM-PM-AM translation, and hence introduces bit error. Equalization techniques commonly used in baseband signaling cannot be applied here, as no clocks are used to synchronize the data. Therefore, crosstalk attenuation must be done to the channel itself.

FSK signaling suffers from the impact from frequency drift of VCO. This can be alleviated by using the injection locking or a multiplier chain to provide a stable signal for both transmitter and receiver, which will be addressed in future work. This work focus on demonstrating crosstalk-immune channel and its potential usage to support dual-channel short-range FSK communication.

Fig. 8 Receiver including (a) LNA, (b) mixer, (c) quadrature VCO, (d) simulated result of LNA, and (e) simulated result of mixer.

Fig. 9 Transmitter including a frequency modulated VCO and a PA.

III. PROPOSED SLOW-WAVE TRANSMISSION LINE

EM-wave radiation in the free space follows dispersion relation of $\omega_0 = ck_0$, where c is the speed of light, and k_0 is the wave vector. By localizing the free electron into spatial cavity, it is possible to squeeze the EM energy inside an ultra-small volume. This will lead to an increase of wave vector k_{sw} , such that the EM wave becomes stationary. In Fig. 1, the phase velocity v_p , defined by the slope of the dispersion curves, approaching zero at some frequencies when $k_{sw} \rightarrow \infty$. Under this circumstance, the dispersion of slow-wave propagation is described by $\omega_{sw} = v_p k_{sw}$, and ω_{sw} is the cut-off frequency where the wave propagation is prohibited. Below ω_{sw} , the wave propagation is slower than that in the free space, which is the speed of light. Therefore, operating in high frequencies, such a field-confined structure exhibits the slow-wave characteristic.

An ultra-thin SW-TL has been reported in board level operating in microwave frequency [14]. Using this concept, a chip-scale SW-TL is designed as shown in Fig. 3(a). It features by a periodic groove with small volume of cavities. The gradient grooves at the interface are necessary for both impedance and momentum matching, as the wave vector of SW-TL is much larger than that in the free space. The

electric-field (E -field) distribution evaluated in the xy -plane is illustrated in Fig. 3(b). As observed, the fields are tightly confined into the grooves, and the field extension towards the y -direction follows an exponential decay, indicating strong field confinement. Such a SW-TL has been implemented in a standard bulk CMOS technology, and the die photo is shown in Fig. 4. The physical length is 1 mm, excluding the pads. The groove depth is $h = 12 \mu\text{m}$ each side, and the gap between groove is $a = 2.4 \mu\text{m}$. Near-field simulation result reveals that a must be minimized for stronger field localization. The periodic pitch d is chosen as $24 \mu\text{m}$ to lower the dispersion curve suitable for 160 GHz broadband communication. The simulated and measured S -parameters are summarized in Fig. 5. Obviously, the use of gradient converter reduces the mode conversion loss and hence reflection S_{11} . Moreover, the measured S_{21} is not degrading as frequency goes up, in contrast to conventional TL structures. This implies the proposed SW-TL is immune to substrate loss. Similar principle has been utilized in the high- Q resonators and high frequency signal sources [15–21].

Based on the above study, a dual-channel SW-TL with $2.4 \mu\text{m}$ channel spacing has been implemented in 65 nm CMOS technology as shown Fig. 6(a). Twisted structure is

Fig. 10 FSK communication of (a) 2 Gb/s single-channel SW-TL TRx, (b) 4 Gb/s single-channel SW-TL TRx, (c) 4 Gb/s dual-channel SW-TL TRx, (d) 2 Gb/s single-channel TL TRx, (e) 4 Gb/s single-channel TL TRx, and (f) 4 Gb/s dual-channel TL TRx.

used to save area, but it still provides an equivalent length of roughly 2 mm. Noted that a 2 mm length is sufficient for a strong coupling at 160 GHz, which qualifies for an evaluation of crosstalk attenuation by the proposed SW-TL. Fig. 6(b) illustrates the E -field distribution. Here, only one channel is excited. Clearly, the aggressor shows negligible EM crosstalk to the adjacent channel, and the fields are tightly confined into the periodic grooves. The measured S -parameters are summarized in Fig. 7. Compared to traditional T-line with the same channel spacing [22, 23], more than 19 dB crosstalk suppression is achieved.

IV. CIRCUIT IMPLEMENTATION

Fig. 8(a) depicts a 3-stage LNA employing cross-coupled capacitor C_c to improve the gain and also reduces the noise figure (NF). A balun is used to serve as a single-ended to differential converter, which also provides impedance transformation for input impedance matching. Transformers are used as inter-stage matching. Compared to transmission line matching commonly used in THz circuit design, transformer has a smaller area and inherently provides DC supply through the center tap. Deep N -well NMOS transistors are used to isolate the substrate noise. MIM capacitor is used here for its higher quality factor than MOM capacitor at 160 GHz. Simulation result reveals that the value of MIM capacitor in the first stage can be chosen as 20 fF to improve both reflection loss and gain. Broadband matching is obtained as well using the capacitor C_c . However, using the same capacitor at the 2nd and the 3rd stage leads to instability. As such, 10 fF capacitance has been chosen for the 2nd and the 3rd stage. All DC biasing are through the center tap of transformer. The S -parameter simulation results are shown in Fig. 8(d). The power gain is 10 dB at 160 GHz while the NF is smaller than 8 dB. The use of transformer coupling increases the bandwidth to more than 40 GHz.

Mixer conversion gain (CG) and NF are sensitive to the parasitic capacitance in the internal nodes. For this reason, three transformers are used, as shown in Fig. 8(b). The input transformers serve as input impedance matching network for both the RF and LO port, while providing DC biasing for the mixer to achieve linear operation over the LO signal level by hard switching. This can be guaranteed by feeding the mixer quad by a large swing differential voltage from the VCO. CG and NF are simulated as shown in Fig. 8(e). 7 dB CG is achieved at near-DC while the NF is clearly

dominated by flicker noise. The 160 GHz quadrature signal generator is shown in Fig. 8(c) [10].

By switching the capacitor bank in VCO, frequency modulation is achieved in transmitter as shown in Fig. 9. V_{tune} is necessary here to align the center oscillation frequency to be equal to that of receiver. The PA design (M3–M8) is similar to LNA, except that the transistor size is larger to generate higher output power [24]. Power combining can be used to enhance the output power [25, 26].

V. DUAL-CHANNEL FSK COMMUNICATION

The 2 mm long dual-channel FSK communication with 2.4 μ m channel spacing are summarized in Fig. 10. First, single-channel transmission is performed, and the results are shown in Fig. 10(a)–(b) and (d)–(e). All the eye diagrams have clear horizontal/vertical eye opening for both 2 Gb/s and 4 Gb/s communication. The SW-TL based TRx has around 2 times vertical eye opening than TL based counterpart. However, as shown in Fig. 10(c), only the SW-TL based 4 Gb/s dual-channel signalling has a clear eye opening, whereas the eye diagram of the TL-based FSK signalling is completely distorted, as shown in Fig. 10(f). As such, reducing channel crosstalk is critical in FSK communication, which can be realized by the proposed SW-TL proposed in this work.

VI. CONCLUSION

A dual-channel FSK communication by exploiting a novel SW-TL is proposed in this paper. The proposed SW-TL achieves field confinement with extraordinary performance to suppress the channel loss and crosstalk by more than 19 dB. Preliminary results reveal that the SW-TL based FSK transceiver can recover error-free 4 Gb/s data even the channel spacing is only 2.4 μ m, demonstrating crosstalk immune communication by the use of the proposed SW-TL.

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