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主動及被動 CMOS 合成波導與電路

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一、中文摘要

本計劃區隔三大類的 CMOS 波導設計,依工作頻率區分如下: (1) 介於 DC 及 f_a 之間。 f_a 為主動 CMOS 合成波導之工作上限頻率，以 0.18μm CMOS 為例約在 5GHz。 在這種主動 CMOS 合成波導為週期結構，由單位細胞(cell)構成; 每一細胞由上下藕合之互補式金屬波導形成 (Complementary-Conducting-Strips Waveguide; 中華民國專利公報中;美國專利申請中); 而每一細胞都銜接上一主動負電阻電路。 如此形成可能是已知波導中在常溫無損耗的傳輸特性之第一例。 (2)被動式毫米波 CMOS 合成波導，具最低工作頻率高於 f_p。以 0.18μm CMOS 技術為例 f_p 約在 60GHz。在當 $f > f_p$，CMOS 之增益不足以形成足夠好的主動電路。 (3) 介於 f_a 及 f_p 之間的窄頻主動式合成波導。 於此頻段負電阻電路將被高效率但窄頻的微波電路取代。

本計劃涵蓋三年之長期研究，研發原創性 CMOS 合成波導而無需改變原有製程。 其發展目標如下: (a) 微小化，無損耗之主動合成波導工作在 $f < fp$。 (b)多元化空間且低損耗之合成波導及轉接電路工作在 $f > fp$。 (c)微小化其頻寬約 10% 之低損耗之主動合成波導工作在 $fa < f < fp$ 之間。 本計劃雖屬基礎 CMOS 合成波導研究，不包含許多可能之應用研究，仍將盡可能拓展合成波導在 smart antenna 或 RFIC 之設計。

關鍵詞：CMOS 合成波導、互補式金屬波導

Abstract

Advance in CMOS technology has positioned CMOS RFIC a dominant IC technology for transceiver block of RF signal processing, replacing the bipolar and GaAs-based IC technologies. Trend toward higher microwave and millimeter-wave regimes is expected for CMOS to take over what were dominated by the III-V technologies traditionally. The distributed waveguides, therefore, become indispensable for designing RF CMOS IC at higher microwave and millimeter-wave frequencies, since inter-stage matching is a necessity for optimal RF signal processing.

Waves propagating in waveguides integrated on CMOS, however, suffer serious degradations in intolerably high attenuation constant and limited range of characteristic impedance. Both microstrip (MS) and coplanar waveguide (CPW), thus, found limited applications for CMOS RFIC designs. This proposal aims to resolve the above-mentioned issues that handicapped CMOS RFIC design from lower to higher microwave frequencies and beyond.

This proposal presents a variety of synthetic CMOS waveguides covering DC to millimeter- wave frequencies to improving CMOS RF circuits and making new RFIC designs and applications. Three regimes of operation for synthesizing CMOS waveguides are specified. First, a broadband, DC to f_a active CMOS waveguide is presented. The upper frequency limit of f_a is 5GHz for a typical 0.18μm CMOS technology and f_a will be higher when CMOS technology advances further to finer photolithography. The synthetic active CMOS waveguide is a periodical guiding structure made of a collection of unit cells, which consists of passive, synthetic complementary-conducting-strips (CCS) waveguide (ROC patent approved, US patent pending) and active negative differential resistance device. To our best knowledge, this is the world's first guiding structure exhibiting loss-free characteristics.

Second is the millimeter-wave CMOS waveguides above f_p, which is the lower bound frequency of passive CMOS waveguides and is typically at 60GHz. Near f_p current 0.18μm CMOS technology is stretched to limit, showing little gain available for RF integration. Thus attention will be focused on passive RF signal processing units on CMOS IC, above f_p. Between f_a and f_p is a wide spectrum for a variety of microwave and millimeter-wave RF communication systems. In this regime, a synthetic active waveguide is proposed for narrowband applications.

This proposal covers three years of continuing efforts on basic researches for CMOS waveguides. The targeted achievements include (a) synthetic, miniaturized, loss-free waveguides / transmission lines for $f \in (0, f_a)$, (b) synthetic, multi-dimensional, low-loss waveguides and transitions for $f > f_p$, (c) synthetic, narrowband, low-loss, active waveguide for $f \in (f_a, f_p)$. Applications of the synthetic active/passive CMOS waveguides are numerous and not included in the scope of this proposal. When applicable, however, the conducted researches may generate useful results for smart antenna and RFIC designs, etc.

The researches are evenly distributed into a three-year period. Year 1 will focus on general design considerations of synthetic CMOS waveguides for $f \in (0, f_a)$ and $f > f_p$. Year 2 will emphasize on synthetic CMOS waveguides for $f \in (f_a, f_p)$ and continue the researches on the other bands. Year 3 intends to design transmission line/waveguide circuits that will demonstrate the applicability of concepts of synthetic CMOS waveguides from lower microwave frequencies to millimeter-wave regime.

Keywords: Synthetic CMOS waveguides,
Complementary -conducting-strips

二、緣由與目的

CMOS technology combining both analog and digital integrated circuits has matured as a dominant IC technology that includes RF (radio frequency) transceiver building block. To date CMOS RFIC reaches 6GHz in the consumer world and approximately 30GHz at research laboratories using. The success of CMOS IC technology as a dominant process can be attributed to the following factors (a) continuing refinement of CMOS IC process toward low cost, (b) performance improvement abiding the Moore's law, and (c) the best technology for SOC (system-on-chip) integration of multi-functional microelectronic system blocks. The complete success of CMOS IC technology in RFIC, however, is not over. Many researchers around the world have tried numerous attempts to reduce the propagation losses of transmission lines, or waveguides in general, integrated on CMOS IC. Popular techniques for reducing the attenuation constants include (a) micromachines substrate and metal layers [1]

(b) high-resistivity substrate and thick low-loss dielectric [2] (c) insulated substrates such as SOS (silicon on sapphire) [3], and (d) patterned ground shields and equivalents [4-5]. Notice that the literatures referenced above reflect only a very small portion of published results in the past 10 years. Nevertheless these papers reflect high degrees of representative works in the field. In summary the CMOS substrates are highly lossy, the metal layers are relatively thin as compared to skin depth, the dielectric spacing between metal layers are also very thin. These factors cause CMOS transmission lines highly dispersive with losses greater than 10dB per wavelength for frequency below 10GHz using typical CMOS process in the present day.

This proposal present an entirely different approach from the above-mentioned researches attempting to develop reasonably good CMOS transmission lines, thus further enhancing the position of CMOS IC technology in the RFIC research and development, particularly at higher microwave frequencies and millimeter-wave regime. The core concepts of this proposal are results of several years of researches sponsored by National Science Council and Ministry of Education of Taiwan. Without resorting to the exotic process modifications based on micromachined techniques and use of insulating substrates, this proposal presents the concepts of synthetic waveguides, which had been successfully implemented in the large leaky-wave array [6], new leaky-wave antennas [7-9], new EME (electric-magnetic-electric) slow-wave structure [10], and recently the synthetic rectangular waveguides [11-12], etc. The synthetic waveguide approach adopts several physical mechanisms. First is modal transition between various waveguide. This had been reported for microstrip and waveguide mode conversion in filter [13], oscillator [14] etc, achieving excellent performance in PCB realizations. Second is the use of mode-coupling effect that results in eigen-value approach for designing new class of waveguides [6,8,9] that open up new applications. Third is the application of periodical structures that show high impedance state in the stopband. These stopband characteristics are, in fact, very complicated in guiding characteristics (with some data to be reported in the next section) in that there are space harmonics and various modal transitions occurring in the stopband. The stopband high-impedance state and its influence in the passband are combined to design neew waveguides, which break the theoretical limit of the conventional waveguides such that the slow-wave factor of waveguide can exceed $\sqrt{\varepsilon_r}$ [10, 11] and TM_{10} waveguide can exist [12]. $\sqrt{\varepsilon_r}$ is the relative dielectric constant of the dielectric material for use in designing waveguides. This proposal combines all these electromagnetic techniques of designing waveguides to combat the CMOS waveguide design without modifying the existing CMOS IC process. Prior to this proposal write up, internal researches show that CMOS microstrip line on PBG ground plane, which is a two-dimensional periodical array to be reported in the [5], shows quality factor Q higher than those using pattern ground shields and Q much better than those simply integrated on CMOS lossy substrates. The synthetic waveguides as reported above have consistently show high Q properties, e.g., Q of 260 for miniaturized TE_{10} mode waveguide at 4GHz and Q of 220 for TM_{10} mode rectangular waveguide at 12GHz in printed-circuit-board technology. Both theoretical and experimental investigations of simple guiding structures in CMOS and PCB have demonstrated the potentials of synthetic waveguides realized in contemporary CMOS IC technology.

三、研究步驟與方法

As briefly discussed in the previous introductory section, the experiences gained successfully in PCB realizations of synthetic waveguides may not be directly applicable for designing synthetic CMOS waveguides.

The difficulties arise for the following reasons:

a) The effects of metal thickness and metal conductivities of the CMOS interconnects are critical for accurate assessment of guiding characteristics of the synthetic waveguides;

b) Guiding structures are usually quite complex when realizing synthetic CMOS waveguides, thus accurate electromagnetic (EM) modelings of these guiding structures are also difficult;

c) The complexities involved in solving EM fields of the proposed guiding structures in CMOS substrates are far beyond the university-generated codes, therefore generalized, commercially available EM solvers such as Ansoft's HFSS should be used frequently. These exercised with great cares, particularly when new guiding structures are under development without prior knowledge of guiding characteristics.

d) CIC CMOS IC foundry service shows less resource for basic researches, and the pressure of first-pass design appears mandatory for researches involving monolithic IC foundry supports.

e) Development of new and innovative guiding structure needs basic and solid understanding of electromagnetic wave-propagations, which are somewhat difficult to attract attentions of students in the present curriculum worldwide.

The CMOS RFIC that integrates RF transceiver building block has reached to 6GHz at present. Most designs of these CMOS RFIC are fundamentally based on lumped LC matching elements. In Appendix A of this section are had reported on LC-free CMOS oscillator, where an effective $1/\lambda_g$ resonator replaced the LC tank and resulted in a miniaturized first pass design. (See Fig. 11 and Fig. 12 of [15]). With such success, this proposal moves one step further, presenting a design of active CMOS transmission line that supports quasi-TEM mode using the so-called CCS TL (complementary-Conducting-Strips transmission line), which was also shown in [15] that demonstrated how the CCS TL could be applied for miniaturization of a rat-race hybrid with nearly good performance when realized in a conventional microstrip mode. (See Fig. 6, Fig. 7 and Fig. 8 of [15] for the comparative studies.) Since the cross-coupled CMOS transistors exhibit negative differential resistance, this proposal presents the world first active transmission line that can produce loss-free propagation characteristics by distributing the negative differential resistance into each unit cell of the CCS TL, thereby forming a synthetic, active CMOS waveguide that is potentially loss-free. Notice that the 5.2GHz CMOS oscillator must have negative differential resistance that overcomes the losses in the CCS TL. When designing CMOS CCS TL loaded with negative differential resistance, we will design unit cells similar to those reported in Fig. of [15], using top metal layer (M6) as the meandered pattern and bottom layer (M3) as the periodical, two-dimensional, ground plane. Each CCS TL is locally connected by M1 and M2 metal layers to the cross-coupled CMOS devices, which form the negative differential resistance circuit. By proper scaling, the 0.18um CMOS technology can yield attenuation constant that approaches $0\mathrm{dB}/\lambda_g$, i.e., loss-free, at 5GHz in our analyses. Thus the first candidate CMOS guiding structure proposed here is the synthetic, active CMOS waveguide operated between DC and upper-limit frequency f_a. If successfully developed, this will be world's first active monolithic transmission line that is loss-free. We expect most microwave circuits based on TL realizations can be designed using this guiding structure, thereby stretching the existing CMOS RFIC to an unprecedented era that conventional microwave hybrids such as phase shifters, couplers, filters, rat-race, etc, can become monolithic in a CMOS fashion.

The skin depth of aluminum at 300K^o is 0.337um at 60GHz, approximately equal to the thickness of metal layers of CMOS interconnect. Therefore we propose synthetic passive waveguides with lower bound frequency f_p at 60GHz. Referring to Appendix B and Appendix C of the attachment in this section, we infer that width of 750um will be sufficient for making CMOS TE_{10} mode rectangular waveguide. The same waveguide could possibility support TM_{10} mode at approximately 110GHz. Since guided-wave electromagnetic energy is primarily confined within the waveguide, the effects of lossy substrates are negligible for the synthetic waveguides. Furthermore, the quasi-TEM type synthetic waveguide like CCS TL can be developed for $f > f_p$. The interface between CCS TL and synthetic rectangular waveguides can be the mode converter described in [15]. Altogether, the synthetic passive waveguide system is relatively low-loss and commensurate with contemporary CMOS IC technology. Notice that at 100GHz, the skin depth is further reduced to 0.261um, rendering waveguides of much higher Q factor.

Between f_a and f_p, synthetic active waveguide is proposed. In this regime, reactively loaded transistor, in NMOS or PMOS, can produce negative differential resistance in a specified region by properly controlling device size and reactive loading in much the same way as designing a microwave oscillator. By so doing, for example, the CCS TL as described in [15] can be loaded by such narrowband negative differential resistance in a cell to cell basis, rendering a periodical structure that is potentially a loss-free active waveguide.

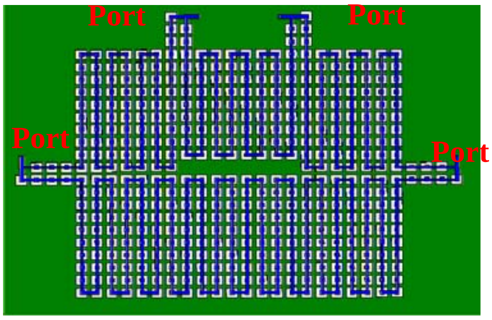
So far the design of synthetic waveguides, whether active or passive, is fundamentally a periodical structure, from which degree of freedom of designing waveguides meeting various types of circuit needs is greatly enhanced. To design these periodical structures, the stopband guiding characteristics should be characterized with cares. [16] documents several representative case studies of periodical structures, showing that the stopband characteristics are for more complicated than what scattering analyses imply. Two classes of periodical structures are reported, one is the weakly agitated type of periodically equal to half wavelength (See Fig.2 of [16]) and the second is a strongly perturbed type of periodicity much small than half wavelength (see Fig. 6 of [16]). The synthetic waveguide to be developed will fall into the latter case. Even so, not every PBG (photonic bandgap) structure is applicable. For example, the UC-PBG (uniplanar compact PBG) structure displays many modal conversions between leaky wave and surface waves, thus narrowing the applicable range of adopting UC-PBG as a high impedance surface (See Fig. 7 and Fig. 8 of [16]). The EME type, however, shows much simpler complex modes generation except at the lower bound of the stopband, where leaky waves exist (Fig. 9 and Fig. 10 of [16]). Therefore evanescent fields exist in most of the stopband region, rendering a low-loss, high impedance surface, which is suitable for low-loss synthetic waveguide design. Throughout the design course of this proposal, the stopband guiding characteristics of the unit cell or the guiding structure must be fully characterized before tape out in a similar way presented in the [16].

四、結果與討論

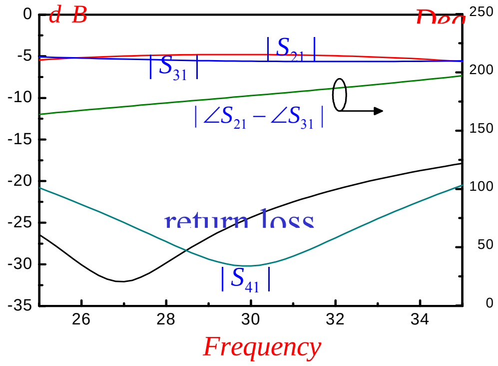
本案執行第一年期計畫，實現了 CMOS 微小化，及無損耗主動合成波導，合計共兩個設計。

(一) 30GHz Rate-Race Hybrid

此 30GHz Rate-Race Hybrid 是利用一種互補式導電片(Complementary Conducting Strip)合成傳輸線[15]來應用在一般 CMOS IC 製程上。它是一種周期性結構，允許靈活控制特性阻抗和慢波係數等受 IC 製程限制的參數並能將電路有效的縮小化。圖一為此 30GHz Hybrid 電路圖。



圖一、Layout of 30GHz Rate-Race Hybrid.



圖二為此 Hybrid 從 25 至 35GHz four ports 散射參數模擬結果。

圖二、 Simulation Results of 30GHz CMOS 180^0 Hybrid.

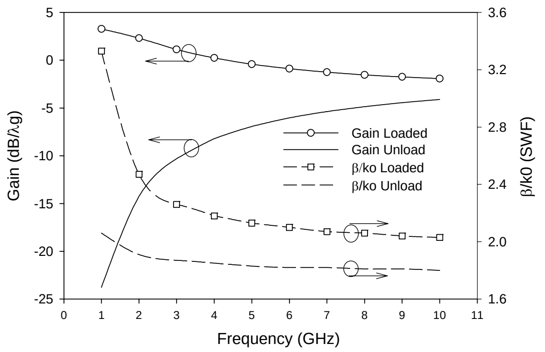
下表整理出此 30GHz CMOS 180^0 Hybrid 模擬結果所達到之規格:

表一、 Specifications of the 30GHz CMOS

Amplitude in-balances	0.6 dB
Return loss	< 20 dB@ 25-33GHz
Isolation	< 20 dB
Phase difference	170^0-190^0@ 29-31GHz

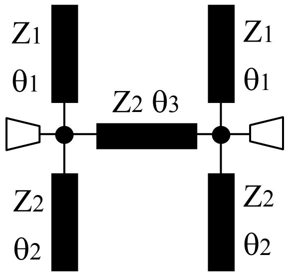
(二) 無損耗 5GHz CCS 主動傳輸線濾波器

於 CMOS 0.18um 製程裡，利用第六與二層金屬型成的 Meandered CCS 被動傳輸線電路(Unloaded)，經由主動的負阻抗電路補償之後(Loaded)。其主動合成波導的特性如圖三所示。在 5GHz 頻率的 SWF 增加約 25%，而且衰減特性由-8.5 dB/λg 補償至接近 0dB/λg。



圖三、主動合成波導的傳輸線特性。

一個 5GHz CMOS 傳輸線帶通濾波器[17]的原型電路，如圖四所示。



$Z_1=58$ $\theta_1=90$ @ 8GHz

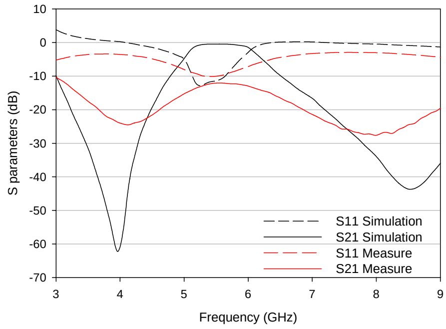
$Z_2=47$ $\theta_2=90$ @ 4.28GHz

$Z_3=47$ $\theta_3=90$ @ 4.862GHz

圖四、5GHz 傳輸線帶通濾波器原型電路。

由上述之主動合成 CMOS 之 CCS 波導結構，來實現原型電路的理論模擬與量測結果整理於圖五。由理論模擬，證實使用 CMOS 合成波導結構，可以實現 silicon 上無損耗的傳輸線濾波器。而量測結果顯示，可能的低頻震盪，可由降低負阻抗電路的補償而改善。後期的研究，將投入穩定的 CMOS 合成波導之濾波器電路的架構開發。

圖五　輸線



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