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Research on Optoelectronic Velocity Matching Technology in Silicon-Based Slow-Light Modulators

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Abstract. High-speed silicon-based on-chip optical interconnection has become an indispensable core technology to support ultra-large-scale high-performance computing and artificial intelligence data processing systems. Traditional silicon traveling-wave Mach–Zehnder modulators, the core electro-optic conversion devices of optical interconnection chips, are plagued by severe optoelectronic velocity mismatch between guided optical waves and high-frequency microwave driving signals, which brings three prominent drawbacks: excessive device footprint, limited electro-optic modulation bandwidth and high overall operating power consumption. Although slow-light waveguides constructed with photonic crystals or Bragg gratings can strengthen light-matter interaction and shrink the length of phase-shifting arms, they making the bandwidth degradation problem more prominent. This paper systematically carries out a comprehensive review on the collaborative optimization technology of slow-light waveguides and slow-wave electrodes for silicon-based slow-light modulators. It first elaborates the internal physical mechanism of optoelectronic velocity mismatch, then compares the structural characteristics, refractive index tuning capacity and radio-frequency loss performance of three mainstream slow-wave electrode schemes. Afterwards, this paper summarizes the comprehensive static and dynamic performance improvements brought by complete optoelectronic velocity matching. Finally, the existing technical limitations of current co-optimized modulators are summarized, and targeted future research directions are put forward, which can provide systematic theoretical guidance for the design of miniaturized, broadband and low-power silicon photonic modulators for next-generation high-density on-chip optical interconnection.

Keywords: Silicon photonics, slow-light waveguide, slow-wave electrode, optoelectronic velocity matching

1. Introduction

With the rapid growth of global data and advances in artificial intelligence, high-speed optical interconnects are seen as a key tech for transforming high-performance computing centres. Because they work so well with CMOS processes, silicon photonics allows for wafer-level, low-cost mass production, making it a vital tech to meet the future demands of fast interconnects and huge computing power. In this setup, silicon-based optical modulators, as main electro-optical devices,

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turn electrical signals into optical ones, setting the stage for things like on-chip optical interconnects, fast data transfer, signal processing, and photonic computing [1].

The demand for data throughput in data centres and high-performance computing interfaces keeps rising. Because they're easy to use, the IEEE has set up intensity modulation/direct detection (IM/DD) systems, specifically 4-level pulse amplitude modulation (PAM-4), as the go-to approach for short-distance optical links. But the naturally slow carrier transmission speed of silicon means there's a big gap between the single-wavelength transmission rate of pure silicon modulators and the 400 Gbps per-channel rate needed for future ultra-fast optical links. Fixing the speed bottleneck of CMOS-compatible pure silicon platforms has become a major issue that urgently needs sorting out in the field of silicon photonics [2].

Conventional silicon-based travelling-wave electrode Mach–Zehnder modulators (MZMs) run into a few major issues in real-world use, which limits their wider adoption in high-performance optical connections. In terms of size, traditional MZMs need long phase-shift arms to get enough phase modulation, taking up lots of chip space, which isn't great for high-density photonic setups. microring modulators (MRMs) are small and use less power per bit, but they only work well at exact resonant wavelengths, so it need external temperature control to stop resonance drift, which ends up using more overall system power. When it comes to operating bandwidth, even with lots of tweaks in silicon modulator speed, practical limits around 67 GHz pop up, making it tricky for silicon photonics to hit Tbps data rates on a single chip. This bandwidth limit mainly comes from the limited plasma dispersion effect in silicon carrier-depletion modulators and high-frequency losses in travelling-wave electrodes. On power use, standard silicon modulators face a natural trade-off between modulation efficiency and power consumption. Getting enough modulation usually means long modulation paths or high driving voltages, which both increase power use. In high-density setups like data centres, power consumption not only affects running costs but also causes big thermal management headaches.

To tackle the issues mentioned, this paper suggests a technical approach of jointly optimising slow-light waveguides and slow-wave electrodes, breaking through the limits of traditional modulators from both optical and electrical perspectives. Slow-light waveguides add periodic micro-nano structures like photonic crystals or Bragg gratings into the waveguide design to drastically slow down the group velocity of light, greatly enhancing light-matter interaction over a short distance. This boosts modulation efficiency, letting it get the same phase modulation with shorter phase shifter lengths and shrinking device size. Slow-wave electrodes, by using travelling-wave electrodes with periodic capacitive loading or inductive compensation, raise the effective refractive index of microwaves to match the group refractive index of light in slow-light waveguides. Matching the speeds of electricity and light is key for broadband operation of travelling-wave modulators — when microwaves and light move at similar speeds along the electrode, they stay in phase over the whole interaction length, boosting modulation efficiency and widening electro-optic bandwidth. Together, slow-light waveguides and slow-wave electrodes effectively slow down both electrical and optical signals, matching light and microwave speeds to achieve efficient, broadband electro-optic modulation in compact devices. This approach offers a fresh way to overcome the performance limits of conventional silicon-based modulators.

This paper aims to take a close look at the main technologies behind collaborative optimisation for slow-light waveguides and slow-wave electrodes in silicon-based slow-light modulators, focusing on three things: First, it goes through the physical mechanism of slow-light waveguides, typical structures, and how they improve modulator performance. Second, it looks into the causes of electro-optic velocity mismatch in travelling-wave electrodes and reviews how slow-wave

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electrodes are designed and put into practice. Third, it talks about the improvements in both static and dynamic performance of slow-light/slow-wave collaborative modulators.

2. Slow-light waveguide technology and application in modulators

2.1. Fundamental principles

Group Refractive Index and Structural Dispersion. The slow-light effect is when light waves move through a medium much slower than in a vacuum. In silicon-based waveguides, this usually happens by adding periodic dielectric structures. As light passes through these structures, its dispersion changes a lot, showing a very flat band structure near the photonic band edge, which significantly slows down the group velocity. The relationship between group velocity and group refractive index is described as follows:

$$V_g = c/n_g, n_g = n + \omega \cdot dn/d\omega \tag{1}$$

where c is the speed of light in vacuum, n is the material refractive index, ω is the angular frequency of light, and dn/dω is the material dispersion term. In slow-light waveguides, the group refractive index ng can reach tens or even hundreds, much higher than the intrinsic refractive index of silicon (approximately 3.5). The slow-light effect mainly arises from two dispersion mechanisms: material dispersion and structural dispersion. Material dispersion originates from the variation of the refractive index of the dielectric medium with optical frequency, while structural dispersion comes from the confinement and manipulation of light propagation by the periodic waveguide structure. In silicon-based slow-light waveguides, structural dispersion is usually dominant — through elaborate design of geometric parameters of photonic crystals or grating structures, ultra-high group refractive indices can be obtained within specific wavelength ranges. Notably, achieving the slow-light effect often incurs certain physical costs. Studies have shown an inverse relationship between increased group delay (i.e., higher group refractive index) and transmittance peaks. Moreover, high group refractive indices are usually accompanied by large group velocity dispersion (GVD), which may cause pulse broadening and distortion. Therefore, in practical slow-light modulator design, comprehensive trade-offs must be made among multiple indicators including group refractive index, photon lifetime, electrical bandwidth, and optical loss.

2.2. Typical slow-light structures

Photonic Crystals, Bragg Gratings, Cascaded Phase-Shifted Bragg Gratings. Based on different slow-light structures, silicon-based slow-light modulators can mainly be split into two types: silicon photonic crystal modulators and silicon waveguide grating modulators.

2.2.1. Photonic crystal waveguides

Photonic crystals (PhC) are man-made micro-nano structures made from dielectric materials arranged in a regular pattern, with their main feature being the photonic bandgap — light of certain frequencies can't pass through the crystal. By adding line defects to two-dimensional photonic crystals, it can make photonic crystal waveguides (PCW), which trap light in the defect area. In these waveguides, it can get super high group refractive indices near the photonic band edge by tweaking the geometry of the defect region (like the air-hole size and lattice spacing), creating a big slow-light effect. Two-dimensional silicon photonic crystal waveguides have higher group refractive

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indices compared to regular silicon waveguides, boosting light-matter interaction. Slow-light modulators using photonic crystal waveguides have been shown to reach 64 Gbps and use as little as 59 fJ/bit [3].

2.2.2. Bragg grating waveguides

Bragg grating waveguides are another key type of slow-light structures. Basically, they work by adding periodic changes to the refractive index in the waveguide core or cladding, as shown in Figure 1. When light travels through the grating, waves that meet the Bragg condition get strongly reflected, creating the slow-light effect near the photonic band edge. Transmissive Bragg grating waveguides have simple designs and work really well with standard CMOS fabrication processes. Research has shown that by properly cascading a set of Bragg gratings, it can build a coupled-resonator optical waveguide (CROW) setup to produce the slow-light effect.

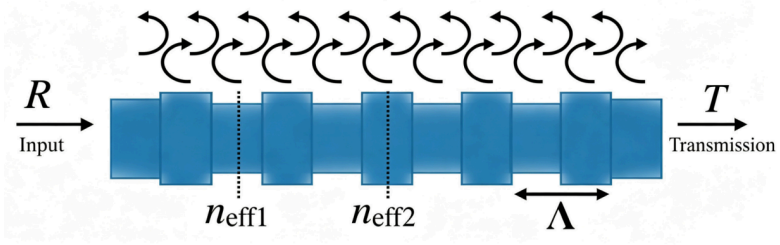

Figure 1. Schematic diagram of the Prague grating waveguide structure

2.2.3. Cascaded phase-shifted bragg gratings

Cascaded phase-shifted Bragg gratings are an improved version of regular Bragg gratings. By adding phase-shift regions periodically, it can create transmission windows (or defect modes) in the photonic bandgap, which can slow down the group velocities linked to these defects. Compared to standard Bragg gratings, cascaded phase-shifted ones give it more design flexibility — it can tweak the size, number, and placement of phase shifts to get low-dispersion slow-light transmission across a wider wavelength range. This is really important for high-speed optical communication because too much group velocity dispersion can seriously limit transmission rates. Silicon modulators using this setup have even hit electro-optic bandwidths over 110 GHz at a compact 124 μm length [4].

2.3. Benefits of slow-light technology to modulators: size reduction

The biggest and most obvious benefit of slow-light technology for silicon-based modulators is making the devices smaller. In standard travelling-wave electrode modulators, the effective length of electro-optic interaction determines how much phase modulation it get. To achieve enough modulation depth, it usually need long phase shifter lengths, which means bigger chips. By slowing down light, slow-light waveguides massively increase the "effective optical path" for light travelling the same physical distance in the waveguide. In other words, light and carriers in the waveguide material interact for longer, letting it get the same phase modulation in a smaller space. This directly means smaller modulators. Making devices smaller brings loads of benefits. For starters, a smaller chip gives it higher integration density, which is essential for building large-scale photonic integrated circuits (PICs). An eight-channel wavelength-division multiplexing silicon-based slow-light modulator chip from Peking University reached an on-chip data rate density of 1.6 Tb/s/mm²

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[5]. Plus, compact devices cut parasitic capacitance and series resistance, boosting high-frequency performance and lowering power use. Smaller size also means cheaper production and better wafer use. But it's worth noting that slow-light tech isn't without trade-offs. High group refractive indices in slow-light waveguides usually come with high propagation loss and big group velocity dispersion. So, when designing practical slow-light modulators, it has got to carefully balance size reduction, modulation efficiency, optical loss, and dispersion control [6]. This is exactly why designing slow-light waveguides and slow-wave electrodes together is valuable — it counteracts negative effects from the optical slow-light effect with electrical optimisation to get the best overall performance.

3. Design of slow-wave electrodes and optoelectronic velocity matching

3.1. Analysis of optoelectronic velocity mismatch in traveling-wave electrodes

The silicon-based traveling wave electro-optic modulator transmits RF microwave signals through traveling wave electrodes, while light waves propagate as optical carriers in silicon waveguides. The mismatch in propagation speed between optical and electrical signals is the core bottleneck that limits device bandwidth. The speed of light propagation in silicon cores is determined by the optical group refractive index, while microwave signals passing through metal electrodes and silicon dioxide buffer layers have independent equivalent microwave refractive indices. For traditional silicon waveguides, their optical group refractive index is much higher than that of microwaves, resulting in significantly slower propagation speed of light waves than microwaves. When optical and electrical signals propagate continuously along the waveguide, phase shift will continue to occur. Under high-frequency modulation conditions, the effective electro-optical coupling efficiency of the two signals in the active region rapidly decreases, resulting in a sharp compression of the 3dB modulation bandwidth. Speed mismatch can also lead to time-domain signal distortion, high-speed symbol modulation phase confusion, and decreased eye diagram quality. Simply extending the electrode length to improve modulation efficiency will further amplify the bandwidth loss caused by speed differences, resulting in a contradictory trade-off between device area and operating bandwidth.

The main aim of photocurrent velocity matching is to get the microwave phase velocity to match the group velocity of light, hitting the ideal matching point where the effective microwave refractive index is the same as the optical group refractive index. When this happens, the optical and electrical signals can travel together through the active waveguide, giving steady electro-optic modulation across the whole active length, boosting modulation efficiency and getting rid of bandwidth limits caused by speed mismatch.

Slow-light waveguides use periodic structures like photonic crystals and gratings to really boost the optical group refractive index, which then widens the gap between the microwave refractive index and the optical group refractive index. Just tweaking the optical waveguide alone doesn't fix the matching issue, so it also needs to boost the microwave refractive index to narrow the difference. It doesn't need the refractive indices to be spot on for engineering purposes; keeping the difference under 0.5 keeps bandwidth loss reasonable, while a difference over 1 causes a noticeable drop in modulation bandwidth. The main limit for electrode design in slow-light modulators is increasing the microwave refractive index via slow-wave electrode structures to match the high group refractive index in slow-light setups.

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3.2. Matching analysis of microwave and optical group refractive indices

Three common ways to boost the microwave refractive index are: segmented electrodes, capacitively loaded electrodes, and T-shaped electrodes.

Segmented electrodes split a continuous travelling-wave electrode into several independent metal segments with isolation gaps, and work with substrate capacitors to slightly increase the microwave refractive index by lengthening the equivalent microwave path. This setup is easy to make but only gives a small boost in the refractive index, so it's mainly good for regular silicon modulators with low group refractive indices and doesn't match well when used with high-group-index slow-light waveguides. Plus, the segmentation gaps cause microwave reflections and add to RF loss.

Capacitively loaded electrodes regularly put metal loading capacitors along the edges of the electrodes, with the lower capacitor plates touching high-dielectric silicon layers. These regular capacitor arrays boost the unit-length distributed capacitance of transmission lines, gradually increasing the microwave refractive index according to transmission line theory. This setup makes it easy to tweak the refractive index by changing capacitor sizes and spacing, but it comes with higher microwave transmission loss and worse RF insertion loss because of the closely packed loading capacitors.

T-shaped slow-wave electrodes are made up of regular arrays formed by long main transmission electrodes with metal branches sticking out sideways. The sideways branches act like built-in capacitors while the main lines make the microwave path longer, giving both capacitive boost and a longer path. They offer better microwave refractive index improvement compared to the other two designs, and can match with high-group-index slow-light waveguides like photonic crystals and gratings. Their consistent periodic layout keeps the transmission line impedance steady and reduces RF reflection loss, making them the best electrode choice for slow-light co-modulators.

3.3. Operating principle and equivalent circuit model of constructed T-shaped electrodes

T-shaped slow-wave electrodes are set up at regular intervals along the path where the light travels. Each unit in the array has a main longitudinal electrode and transverse T-shaped metal branches at right angles. As microwaves move along the main electrode, the transverse branches create parallel-plate capacitors with the underlying silicon and silicon dioxide layers, periodically adding distributed capacitive loads that significantly boost the unit-length capacitance and slightly raise the transmission line's inductance. This slows down the microwave phase velocity and increases the effective refractive index. It can adjust the microwave refractive index to match the group refractive index of slow-light waveguides by changing the T-branch length, array spacing, and metal thickness. The structure keeps the standard 50 Ω RF impedance, reducing high-frequency signal reflections and suiting high-speed on-chip optical interconnect systems.

Each periodic T-shaped electrode works like a lumped RLC unit, with lots of repeated sections forming a full distributed-parameter transmission line model. The main longitudinal electrode acts like series-connected inductance and metal resistance, while the T-shaped transverse branches act like parallel distributed capacitance and dielectric leakage conductance. The silicon dioxide buffer and silicon base add extra parallel capacitance. It can get an expression for the equivalent microwave refractive index from the unit impedance formula, which clearly shows that bigger T-branch sizes increase capacitance and raise the microwave refractive index, giving a solid theoretical basis for optimising electrode designs in simulations.

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4. Performance improvements of co-optimized slow-light modulators

4.1. Influence of optoelectronic velocity matching on electro-optic modulation bandwidth

The 3dB electro-optic modulation bandwidth is the main measure for checking how fast modulators can perform, and their top limit is set by a mix of optoelectronic velocity mismatch and microwave transmission loss. In typical slow-light modulators without velocity matching, slow-light setups boost the optical group refractive index and slow lightwave movement way below microwave speed, cutting the effective modulation interaction length as frequency rises and limiting device bandwidth just because of velocity mismatch. Using T-shaped slow-wave electrodes to match microwave and optical group refractive indices lets light and electrical signals move together along the whole active waveguide length, completely getting rid of bandwidth drop caused by velocity mismatch. Then, the device's natural bandwidth is only limited by microwave transmission loss. With the same device length and slow-light waveguide conditions, matched slow-wave electrodes increase modulation bandwidth. Plus, velocity matching gets around the usual compromise between device size and bandwidth: slow-light setups shrink waveguide size while slow-wave electrodes ensure high bandwidth, letting devices be both smaller and work faster for high-density on-chip optical connections.

4.2. Static performance analysis

Static device performance is measured through three main indicators: insertion loss, extinction ratio, and optical bandwidth. Insertion loss covers both optical transmission loss and RF microwave loss. Optical loss comes from the structural scattering of slow-light gratings and photonic crystals as well as the sidewall roughness of silicon waveguides. T-shaped metal branches slightly increase microwave ohmic loss, but optoelectronic matching shortens the active waveguide length and effectively reduces optical transmission loss. After full optimisation, the total insertion loss of co-optimised modulators can be kept within 3 to 5 dB, beating conventional travelling-wave modulators with the same bandwidth.

The extinction ratio is directly set by how efficiently the electro-optic modulation works. Slow-light effects boost the overlap between optical fields and RF electric fields, while slow-wave electrodes allow full synchronous modulation to make the most of the active modulation area. The change in light intensity caused by the modulation voltage increases significantly. Compared to normal silicon modulators, co-optimised slow-light slow-wave devices give a much better extinction ratio, improving optical signal contrast and reducing bit errors at the receiving end.

Optical bandwidth is limited by the structural dispersion characteristics of slow-light waveguides. Photonic crystals and cascaded phase-shifted gratings have a set effective operating range; outside this range, the group refractive index drops quickly and slow-light gains disappear. T-shaped slow-wave electrodes only change microwave transmission characteristics without affecting waveguide dispersion or narrowing optical bandwidth. Velocity matching removes high-frequency electro-optic coupling loss, letting the device maintain high-speed modulation across the full optical bandwidth of slow-light structures and make full use of their wide operating range benefits.

4.3. Dynamic performance analysis

Dynamic transmission performance is looked at in terms of eye diagram features, transmission rate, and extra effects from the equaliser. Eye diagrams give a clear picture of high-speed digital signal

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quality. In slow-light modulators without matching speeds, continuous phase shifts between light and electricity at high frequencies cause inter-symbol crosstalk, leading to shrunken, distorted eye diagrams and increased signal jitter. After optoelectronic matching using slow-light and slow-wave co-design, the modulation phases of all symbols stay even, effectively reducing time-domain signal distortion, opening up the eye diagram much more, sharply lowering signal jitter, and creating clear boundaries between high and low electrical levels.

Expanding bandwidth directly helps with faster single-channel signal transmission. Co-optimised modulators made using well-established silicon photonic processes can reliably send distortion-free PAM4 high-speed signals at 100 Gbit/s, whereas standard slow-light modulators hit clear speed limits. For multi-channel parallel optical interconnect chips, this co-optimisation approach really improves the overall chip data throughput.

Velocity mismatch in traditional modulators causes high-frequency signal loss, so it usually need complex feed-forward equalizers to make up for it. These equaliser circuits take up chip space and use more power. The slow-light slow-wave optimised structure gets rid of the high-frequency drop from velocity mismatch, smoothing out the device frequency response. Simple, low-order equalisers are enough to meet the same transmission needs, which cuts down power use and saves space on the photonic chip [7, 8].

5. Conclusion

Targeting the practical application requirements of high-speed silicon-based on-chip optical interconnections, this paper addresses the inherent technical bottlenecks of conventional silicon electro-optic modulators, including large device footprint, limited operating bandwidth and excessive system power consumption. It systematically sorts out the technical system of optoelectronic velocity matching for silicon-based slow-light modulators, elaborates the underlying mechanism of collaborative optimization between slow-light waveguides and slow-wave electrodes, as well as the variation rules of multi-dimensional device performance metrics. Core research conclusions are summarized based on existing published domestic and international literature: Conventional silicon traveling-wave electrode modulators inherently suffer from velocity mismatch between optical and electrical signals. The introduction of slow-light structures increases the optical group refractive index and further widens the velocity gap between lightwaves and microwaves, which aggravates bandwidth limitations. Such issues cannot be fundamentally resolved merely by optimizing waveguide structures. Segmented electrodes, capacitively loaded electrodes and T-shaped slow-wave electrodes are all capable of boosting the equivalent microwave refractive index. Among them, periodic T-shaped slow-wave electrodes feature wide tunability of refractive index and outstanding radio frequency (RF) transmission performance, making them the optimal choice for matching slow-light waveguides with high group refractive indices. The distributed RLC equivalent circuit model of T-shaped electrodes enables quantitative analysis of the variation rules of microwave refractive index, supporting precise design to match the microwave refractive index with the group refractive index of slow-light waveguides. The combination of slow-light waveguides and T-shaped slow-wave electrodes to realize optoelectronic velocity matching can comprehensively improve the overall performance of modulators. Specifically, the electro-optic 3dB bandwidth is significantly extended, the extinction ratio is optimized while the insertion loss remains within a reasonable range. Meanwhile, the eye diagram quality of dynamic transmission is enhanced, the single-channel high-speed transmission rate exceeds 100 Gbit/s, and the hardware overhead of on-chip equalizer circuits is reduced. The design goals of miniaturization, high-speed operation and low power consumption can be achieved simultaneously.

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The collaborative optimization scheme of slow-light and slow-wave structures breaks the bandwidth bottleneck of modulators from the fundamental propagation mechanism of optical and electrical signals, balances device footprint and high-speed transmission performance, and provides a reliable and feasible technical route for next-generation modulators applied in high-density on-chip high-speed optical interconnections.

Based on the literature review and theoretical analysis carried out in this paper, future research can be explored in four major directions: integrated collaborative design of composite structures, integration of low-loss novel electrode materials, development of multi-channel array devices, and joint design of drivers and modulators. At present, slow-light waveguides and T-shaped slow-wave electrodes are mostly designed and optimized separately in a stepwise manner. Future research can establish a multi-physics theoretical framework for joint optoelectronic analysis to synchronously optimize the grating period of photonic crystals and structural parameters of T-shaped electrodes. Triple collaborative optimization of optical mode fields, microwave fields and propagation velocities can be realized to further reduce overall device size and mitigate microwave transmission loss. Aluminum and copper are widely adopted as fabrication materials for existing T-shaped slow-wave electrodes, which suffer from severe ohmic loss under high-frequency operation. Subsequent research may fabricate slow-wave electrodes using low-loss conductive materials such as gold and graphene. Combined with silicon photonic platforms heterogeneously integrated with lithium niobate, the electro-optic advantages of both materials can be integrated to further broaden the operating bandwidth of modulators. This paper only conducts theoretical and performance analysis on single-channel modulation units. Follow-up work can design arrayed slow-light slow-wave co-optimized modulators, with a focus on suppression strategies for microwave and optical crosstalk between channels to meet the development demands of multi-channel parallel high-speed optical interconnection chips. Comprehensive theoretical analysis of on-chip integration between RF drive amplifiers and slow-light slow-wave modulators can be implemented to investigate the matching characteristics between driver circuit impedance, bandwidth and modulators, so as to optimize the overall power consumption and transmission performance of the entire optical transmitting unit.

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