Toward Scalable Photonic RF Front-Ends: Stability and Thermal Management in Multi-Carrier Generation for Satellite Flexible Payloads

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ABSTRACT

We present a stability analysis of a microwave photonic multi-carrier radio frequency (RF) generator operating across the Ka, Q, and V bands. The system, developed under the ESA-funded THORMUX project (Tunable Photonic RF Demultiplexer for Broadband Satellites), targeting the realization of a 4-channel photonic MUX/DEMUX with dynamic tunability in both center frequency and bandwidth, addressing the growing demand for fully reconfigurable RF front-ends in next-generation satellite payloads. A central feature of the system is its realization using hybrid integration technology on a photonic integrated circuit (PIC) based in low-loss Si_3N_4 TriPleX® platform, offering substantial advantages in size, weight, and power (SWaP) for space applications. Each channel employs an optically generated local oscillator based on heterodyning two tunable lasers, with a total of five lasers integrated together in the chip. This work investigates key challenges related to frequency stability as the system scales to multiple channels, focusing on frequency allocation and thermal effects. We demonstrate best-case frequency drifts below ±25 MHz in a free-running regime over a 24-hour measurement period. Using infrared imaging, we characterize the thermal emission of the integrated lasers to correlate heat distribution with RF frequency drift. We further propose design optimizations to improve scalability and thermal management, which directly impact long-term frequency stability and overall system performance.

Keywords: microwave photonics (MWP), photonic integration, satellite communications (SatComs), satellite flexible payload, silicon nitride

1. INTRODUCTION

The increasing demand for flexible and high-throughput satellite communications is driving the development of reconfigurable radio frequency (RF) payloads capable of operating over wide bandwidths and multiple frequency bands. In particular, the migration toward higher frequency ranges such as the Ka-, Q-, and V-bands enables higher data rates and more efficient spectrum utilization but also introduces significant challenges in terms of RF hardware complexity, stability, and scalability. Conventional electronic RF front-ends face growing limitations in these bands due to increased losses, reduced tunability, and stringent size, weight, and power (SWaP) constraints, which are especially critical for spaceborne platforms [1].

Microwave photonics has emerged as a promising technology to address these challenges by exploiting the wide bandwidth, low loss, and inherent flexibility of optical systems for RF signal generation, processing, and distribution [2]. In particular, photonic techniques for RF frequency generation based on optical heterodyning offer a scalable and highly tunable approach to implement local oscillators and frequency conversion stages in satellite payloads [3]. These approaches are well suited for next-generation flexible payload architectures, where dynamic reconfiguration of channel bandwidths and center frequencies is required to adapt to varying traffic demands [4]. Recent advances in photonic integration have further strengthened the case for microwave photonic RF front-ends. Integrated photonic platforms enable compact, robust, and power-efficient implementations that are compatible with space qualification requirements. Among these, low-loss silicon nitride (Si_3N_4) technologies have attracted particular attention due to their excellent optical performance, thermal stability, and compatibility with hybrid integration of active components such as lasers and modulators [5]. By integrating

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multiple optical sources and passive components on a single photonic integrated circuit (PIC), it becomes possible to realize multi-channel RF generation architectures with reduced system complexity and improved SWaP characteristics.

Despite these advantages, the scalability of photonic RF generators to multiple simultaneous channels introduces new challenges that must be carefully addressed. In systems relying on optical heterodyning, the stability of the generated RF carriers is directly linked to the frequency stability of the optical sources [6]. As the number of integrated lasers increases, mutual thermal interactions, heat dissipation, and frequency allocation strategies become critical factors that can impact long-term stability and overall system performance. These effects are particularly relevant in free-running or minimally controlled regimes, which are attractive from a system simplicity and power consumption perspective. In this context, this work investigates the stability and thermal behavior of a multi-carrier photonic RF generator developed within the framework of the ESA-funded THORMUX project, targeting flexible RF front-ends for broadband satellite payloads [7]. The system is implemented using a hybrid integrated Si_3N_4 PIC and supports multiple independently tunable RF channels covering the Ka-, Q-, and V-bands. Rather than focusing on ultimate performance figures, this contribution emphasizes the analysis of frequency stability as the architecture scales to multiple channels, with particular attention to thermal effects arising from the integration of several tunable lasers on a single chip.

The remainder of this paper is organized as follows. Section 2 briefly describes the photonic RF generator architecture and its implementation on a hybrid integrated platform. Section 3 presents the experimental setup and characterization methodology used to assess frequency stability and thermal behavior. Section 4 discusses the observed frequency drift characteristics and their correlation with thermal emission and outlines potential design strategies to improve scalability and robustness. Finally, Section 5 summarizes the main conclusions and provides an outlook toward future developments.

2. INTEGRATED LASER SOURCES FOR MULTI-CARRIER GENERATION

The photonic RF generator investigated in this work relies on a set of integrated tunable laser sources that provide the optical tones required for heterodyne-based RF carrier generation. Rather than describing the complete system architecture, this section focuses on the characteristics of the laser subsystem, as it plays a central role in determining the frequency stability of the generated RF signals. The laser sources are implemented using a hybrid integration approach on a low-loss silicon nitride (Si_3N_4) photonic integrated circuit (PIC). In this approach, active III–V gain chips are integrated onto the passive Si_3N_4 waveguide platform, combining the low propagation loss and thermal robustness of the passive circuitry with the wavelength agility of semiconductor lasers [8]. This technology enables the co-integration of multiple tunable lasers on a single chip, which is a key requirement for scalable multi-channel RF generation. A total of five tunable lasers are integrated on the PIC, allowing the generation of multiple optical tones that can be paired to produce independent RF carriers through optical heterodyning. Each laser is designed to operate over a broad tuning range, enabling flexible selection of optical frequencies and, consequently, RF carrier frequencies spanning the Ka-, Q-, and V-bands. Fine wavelength tuning is achieved via integrated thermal actuators, which provide continuous frequency control while maintaining a compact footprint.

From a stability perspective, the close physical proximity of multiple lasers on the same PIC introduces both opportunities and challenges. On one hand, the shared substrate and packaging environment can reduce sensitivity to external perturbations such as ambient temperature fluctuations. On the other hand, localized heating associated with laser operation and tuning can give rise to thermal crosstalk between adjacent sources, potentially affecting their optical frequencies over time. These effects become increasingly relevant as the number of integrated lasers grows and as the system operates in free-running or lightly stabilized conditions. In the present implementation, the lasers are operated without active frequency locking, reflecting a realistic scenario for space-compatible systems where simplicity, robustness, and power efficiency are critical design drivers. Under these conditions, optical frequency stability is governed by a combination of intrinsic laser characteristics, thermal management at the chip level, and mutual interactions between neighboring laser elements. Understanding these mechanisms is therefore essential to assess the scalability of multi-laser photonic RF generators. The experimental analysis presented in this work focuses on monitoring the long-term frequency behavior of the lasers and correlating it with thermal emission patterns observed at the chip level. By isolating the laser subsystem from higher-level system functions, this approach provides insight into fundamental stability limitations and informs future design strategies aimed at improving thermal isolation, heat spreading, and frequency robustness in multi-channel photonic RF front-ends.

3. EXPERIMENTAL SETUP AND CHARACTERIZATION METHODOLOGY

The experimental characterization presented in this work focuses on evaluating the frequency stability of the integrated laser sources and the corresponding optically generated RF carriers. The measurement approach is designed to assess long-term frequency behavior in a multi-laser photonic integrated circuit, under operating conditions relevant to flexible satellite payloads. The photonic integrated circuit is mounted on a temperature-controlled carrier and operated under standard laboratory ambient conditions. Each laser is independently biased and thermally tuned using dedicated electrical control lines, enabling precise adjustment of the optical frequencies required for heterodyne RF generation. All lasers are operated in a free-running regime, without active optical or RF frequency locking, to evaluate intrinsic stability and potential interactions arising from multi-laser integration.

Optical heterodyne signals are generated by combining selected pairs of laser outputs on-chip and detected using a high-speed photodiode. The resulting RF signals are routed to external measurement instrumentation for spectral analysis. Frequency stability is characterized by monitoring the center frequency of the generated RF tones over extended time intervals, allowing the extraction of slow frequency drift components that are particularly relevant for long-duration satellite operations. The measurements are performed over time scales ranging from several hours to up to 24-hours, enabling the observation of long-term trends while avoiding the influence of short-term noise processes. This methodology provides a representative assessment of system-level frequency stability without relying on complex stabilization schemes and serves as a basis for evaluating the scalability of photonic RF generators based on multiple integrated laser sources.

4. FREQUENCY STABILITY RESULTS AND DISCUSSION

Figure 4-1 compares the optically generated RF beat notes obtained from pairs of lasers separated by a larger physical distance on the photonic integrated circuit with those generated by lasers located in close proximity.

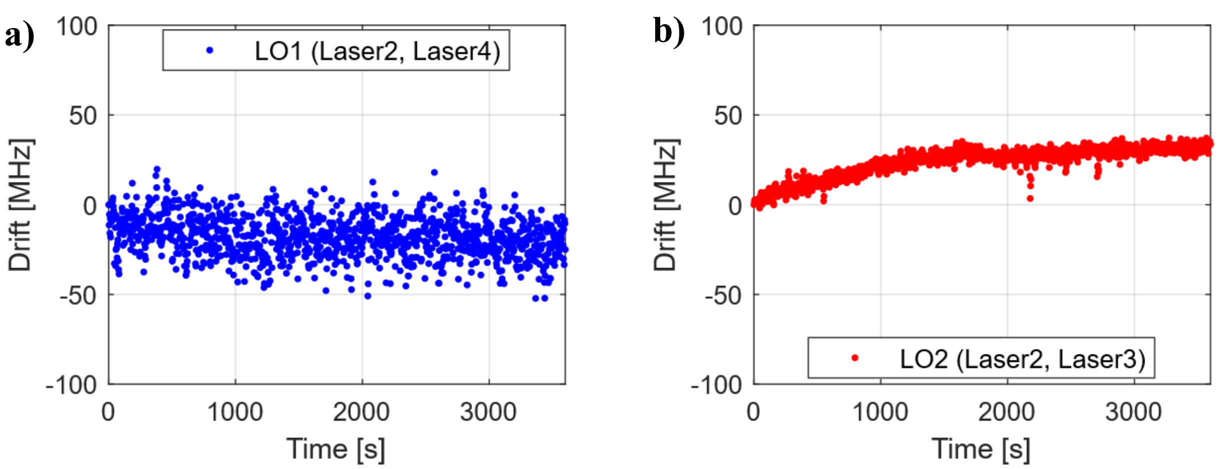

Figure 4-1. Optically generated RF beat notes obtained from different pairs of integrated lasers. (a) RF beat note generated using a pair of lasers separated by a larger physical distance on the photonic integrated circuit, showing increased frequency excursions over time. (b) RF beat note generated using neighboring lasers, exhibiting reduced frequency fluctuations and improved relative stability.

Figure 4-1 (a) shows the RF beat note produced by a pair of spatially separated lasers, which exhibits relatively large excursions over time, reaching values on the order of ±50 MHz. In contrast, Figure 4-1 (b) presents the beat note generated using neighboring lasers, where the observed frequency fluctuations are significantly reduced and remain within approximately ±25 MHz. This comparison indicates that local perturbations affecting the individual laser frequencies are more strongly correlated for closely spaced sources, resulting in improved relative frequency stability in the heterodyne signal.

To further investigate the temporal evolution of the frequency drift, long-term measurements were performed over a 24-hour period, as shown in Figure 4-2. The measurement started at 10:00 a.m., coinciding with the onset of the daily increase in ambient laboratory temperature. As time progresses toward midday, a gradual increase in the beat frequency can be observed, following a well-defined underlying trend. To interpret this behavior, the long-term drift can be regarded as a slow-varying trend onto which faster short-term fluctuations are superimposed. This trend was identified by considering the envelope defined by the maximum and minimum frequency excursions over time and extracting the corresponding mean evolution, which provides a representative indication of the dominant drift component.

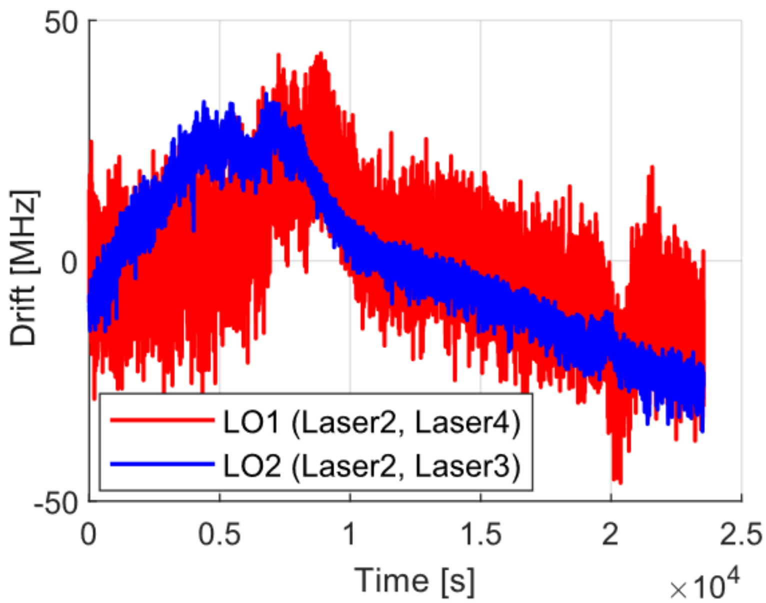

Figure 4-2. Long-term evolution of the optically generated RF beat frequency measured over a 24-hour period. The measurement started at 10:00 a.m. A slow frequency drift can be observed over time, following an underlying trend that is consistent with ambient temperature variations throughout the day. Short-term frequency fluctuations are superimposed on this long-term trend, reflecting the relative stability of the laser pair under free-running operation.

The comparison between the 1-hour and 24-hour measurements demonstrates that the mechanisms governing relative frequency stability are preserved across time scales. While slow environmental temperature changes introduce a common drift component affecting the absolute optical frequencies, the relative stability of the RF beat note is largely determined by the degree of correlation between the two lasers. As a result, laser pairs located closer to each other on the photonic integrated circuit consistently produce more stable RF beat notes, both in short-term and long-term operation.

These results highlight the importance of laser placement and physical proximity in the design of scalable photonic RF generators. Even under free-running operation and in the presence of ambient temperature variations, closely spaced laser pairs enable relative frequency stability below ±25 MHz over extended periods, without the need for active stabilization. This observation underscores the role of integrated layout and thermal co-design as key enablers for multi-carrier photonic RF front-ends targeting flexible satellite payloads.

5. CONCLUSIONS

This work has presented an experimental study on the frequency stability of a multi-carrier photonic RF generator based on integrated tunable laser sources. The results demonstrate that the integration of multiple lasers on a single photonic platform represents a highly attractive approach for the realization of flexible RF front-ends targeting next-generation satellite payloads. The ability to generate multiple RF carriers through optical heterodyning, while maintaining a compact and scalable implementation, is a key advantage of this approach. Experimental measurements performed under free-running operation show that the relative frequency drift of optically generated RF beat notes remains within a range of a few tens of megahertz. Laser pairs located in close physical proximity consistently exhibit improved stability, with frequency excursions below approximately ±25 MHz over both short-term and long-term observation windows. Even for spatially separated laser pairs, the observed drift remains on the order of a few tens of megahertz, highlighting the inherent robustness of the integrated multi-laser platform.

Although no active frequency stabilization was employed in the present experiments, the measured drift levels indicate that the system is well suited for integration with practical stabilization techniques. Operating in a free-running regime with limited frequency excursions significantly relaxes the requirements on the locking range in injection locking schemes, as well as the loop bandwidth and dynamic range constraints in optical phase-locked loop (OPLL) implementations. As a result, the use of integrated multi-carrier photonic sources can simplify the design of stabilization subsystems while improving overall system robustness and power efficiency. These findings underline the potential of integrated multi-laser photonic RF generators as a viable and scalable solution for flexible satellite payload applications. Future work will focus on the implementation and evaluation of stabilization strategies tailored to this architecture, as well as on further optimization of laser placement and thermal management to enhance long-term frequency stability.

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