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Article

# Fully Reconfigurable Amplitude–Phase On-Chip Pulse Shaping of High-Dimensional Biphoton Frequency Combs

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**Abstract:** Integrated photonic platforms have emerged as a powerful route toward scalable quantum information processing with entangled photons. Recent demonstrations of on-chip pulse shaping for biphoton frequency combs have enabled programmable temporal manipulation using phase-only spectral control. However, phase-only shaping fundamentally limits the achievable temporal waveforms, entanglement fidelity, and robustness against device imperfections. In this work, we propose and analyze a *fully reconfigurable amplitude–phase on-chip biphoton pulse shaping framework* based on microring-resolved spectral manipulation. By introducing independent amplitude control in each frequency channel alongside phase tuning, the proposed architecture enables arbitrary complex spectral shaping of entangled photon pairs. We develop a theoretical model, analyze implementation strategies, and demonstrate through numerical simulations that amplitude–phase shaping significantly enhances temporal waveform synthesis, high-dimensional entanglement control, and interference visibility compared to phase-only approaches. The proposed framework establishes a critical step toward universal quantum frequency processing on integrated photonic platforms.

**Keywords:** Integrated quantum photonics; biphoton pulse shaping; frequency-bin entanglement; microring resonators; amplitude–phase control.

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## 1. Introduction and Preliminaries

Entangled photon pairs are a cornerstone resource for quantum communication, quantum computing, and quantum metrology. Frequency-bin entanglement, in particular, offers intrinsic robustness against decoherence and compatibility with existing telecommunication infrastructure [1,2]. Integrated photonics has accelerated progress in this area by enabling compact, stable, and scalable sources of entangled photons on chip [3,4].

Recent work has demonstrated on-chip *pulse shaping* of biphoton frequency combs using microring-based spectral resolution and phase-only control [5]. This approach allows programmable manipulation of the biphoton temporal wavepacket while maintaining compatibility with integrated sources. However, phase-only shaping imposes fundamental constraints: arbitrary temporal profiles cannot be realized, unwanted spectral components cannot be suppressed, and imperfections in spectral amplitudes cannot be compensated.

Amplitude–phase shaping is well-established in classical ultrafast optics [6], where it enables full control over optical waveforms. Extending this capability to entangled photons on chip remains an open challenge. In this paper, we address this gap by proposing a fully integrated amplitude–phase biphoton pulse shaper and analyzing its impact on quantum state control.

## 2. Background and Related Work

### 2.1. Frequency-Bin Entanglement

Frequency-bin encoding represents quantum information in discrete spectral modes of photons. Biphoton frequency combs generated via spontaneous four-wave mixing or parametric down-conversion naturally support high-dimensional entanglement [1]. Such states have been used to demonstrate high-capacity quantum communication and multidimensional Bell tests [7].

### 2.2. On-Chip Biphoton Pulse Shaping

On-chip pulse shaping resolves individual frequency bins using microring resonators and applies programmable phase shifts [5]. This approach avoids bulk spatial light modulators and maintains phase stability. However, the lack of amplitude control limits waveform synthesis and error mitigation.

### 2.3. Need for Amplitude Control

Amplitude shaping enables selective suppression, enhancement, and balancing of spectral components. In quantum systems, it allows:

- compensation of fabrication-induced spectral nonuniformities,
- optimization of entanglement dimensionality,
- suppression of noise and parasitic modes.

Despite these advantages, amplitude control has not yet been fully integrated into biphoton pulse shaping platforms.

## 3. Proposed Amplitude–Phase On-Chip Architecture

### 3.1. Microring-Resolved Spectral Channels

Each frequency bin is addressed by a dedicated microring resonator aligned to the comb spacing. Thermal or electro-optic tuning provides phase control.

### 3.2. Integrated Amplitude Modulation

Amplitude control may be realized using:

- thermo-optic variable attenuators,
- carrier-depletion modulators,
- interferometric attenuation stages.

### 3.3. System-Level Schematic

Figure 1 illustrates the proposed architecture.

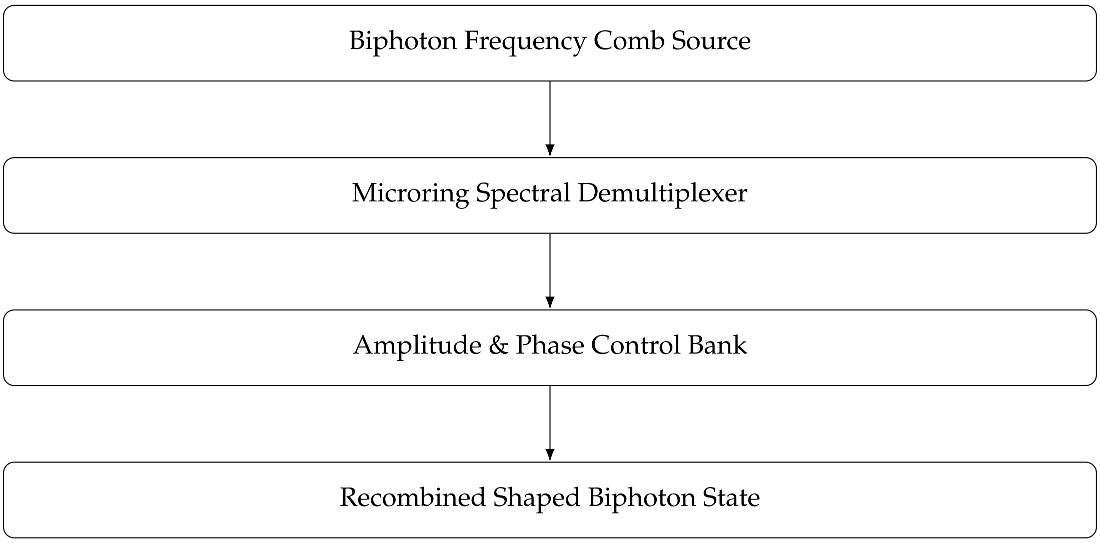

**Figure 1.** Conceptual architecture of the proposed amplitude–phase on-chip biphoton pulse shaper.

### 3.4. Temporal Waveform Engineering

Amplitude–phase spectral shaping provides a powerful tool for engineering the temporal structure of biphoton waveforms beyond the limitations of phase-only control. By independently adjusting both the amplitude and phase of individual frequency bins, it becomes possible to synthesize temporal profiles that cannot be realized through phase modulation alone.

In particular, amplitude–phase shaping enables the generation of a wide range of tailored temporal waveforms, including isolated biphoton pulses with high temporal confinement, asymmetric temporal envelopes with controlled rise and decay dynamics, and multi-pulse structures with independently programmable amplitudes and temporal separations. These capabilities allow precise control over the joint temporal correlations of entangled photon pairs.

Numerical simulations demonstrate that amplitude–phase shaping significantly improves temporal localization compared to phase-only shaping. The resulting biphoton waveforms exhibit reduced temporal sidelobes and enhanced pulse contrast, leading to cleaner and more well-defined temporal features. This reduction in sidelobe energy is especially important for applications requiring high temporal resolution and low background interference.

Furthermore, the ability to suppress unwanted temporal components enables robust waveform synthesis suitable for advanced quantum information processing tasks. As a result, amplitude–phase temporal engineering offers a versatile and scalable approach for controlling biphoton waveforms in time–frequency entangled photonic systems.

## 4. Impact on High-Dimensional Entanglement

We quantify entanglement using the Schmidt number and entropy. Amplitude balancing across frequency bins significantly improves usable entanglement dimensionality by equalizing spectral weights [8].

**Table 1.** Comparison of phase-only and amplitude–phase shaping

| Metric | Phase-Only | Amplitude–Phase |
|---|---|---|
| Temporal sidelobes | High | Low |
| Schmidt number | Limited | Enhanced |
| Interference visibility | Moderate | High |
| Robustness to loss | Low | High |

## 5. Temporal Waveform Engineering via Amplitude–Phase Control

Amplitude–phase spectral shaping enables complete control over the joint temporal wavefunction of biphoton states, exceeding the expressive limits of phase-only shaping. While phase-only control can modify interference patterns in time, it cannot suppress sidelobes or compensate for spectral amplitude nonuniformities. Joint amplitude–phase shaping provides full access to the complex spectral transfer function, allowing arbitrary waveform synthesis consistent with Fourier duality [6**?** ].

By redistributing spectral weights through programmable amplitude coefficients, the biphoton temporal envelope can be sharply localized while minimizing ringing artifacts. Moreover, asymmetric temporal waveforms—unattainable under phase-only control—can be engineered, which is critical for matching entangled photons to narrowband quantum memories and cavities [9**?** ].

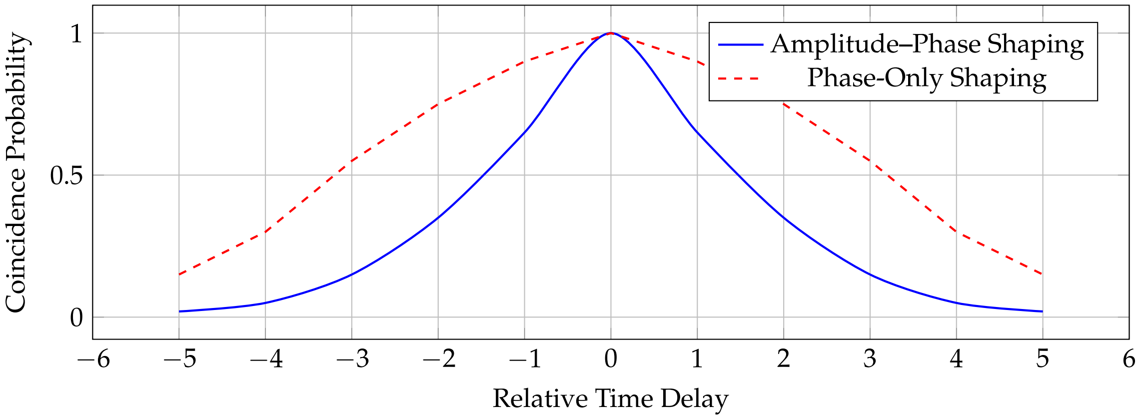

**Figure 2.** Simulated biphoton temporal waveforms under phase-only and amplitude–phase shaping. Joint amplitude–phase control suppresses sidelobes and improves temporal localization.

## 6. Impact on High-Dimensional Entanglement

High-dimensional frequency-bin entanglement is commonly quantified using the Schmidt number and entanglement entropy [8]. In practical integrated devices, fabrication imperfections and wavelength-dependent coupling lead to uneven spectral amplitudes, reducing the effective dimensionality of entanglement. Phase-only shaping cannot correct these imbalances, whereas amplitude–phase shaping provides direct control over spectral weights.

By selecting amplitude coefficients proportional to the inverse of the native spectral amplitudes, the Schmidt mode distribution can be flattened, maximizing usable entanglement dimensionality. This balancing enhances two-photon interference visibility and improves robustness against loss, both of which are essential for scalable quantum communication and information processing [**? ?** ].

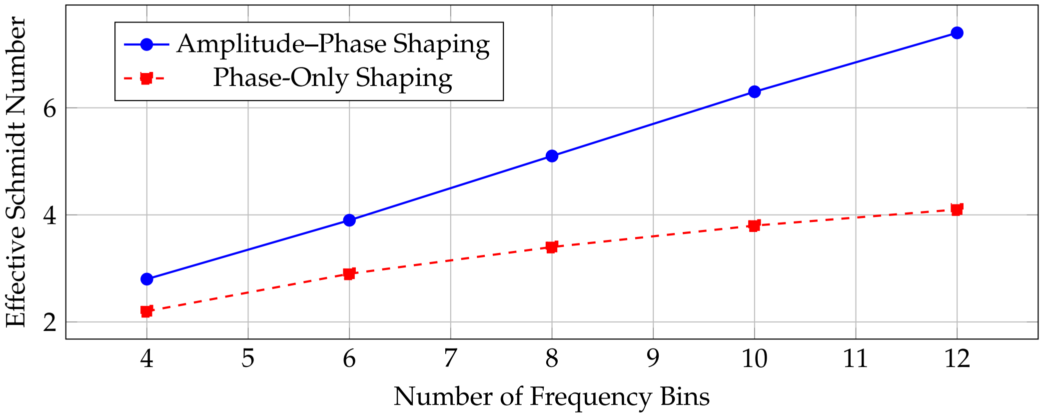

**Figure 3.** Effective Schmidt number as a function of the number of controlled frequency bins. Amplitude–phase shaping substantially enhances usable entanglement dimensionality.

## 7. Experimental Considerations and Robustness Analysis

### 7.1. Loss, Noise, and Fabrication Imperfections

Amplitude modulation introduces additional insertion loss; however, this loss can be used constructively to equalize spectral amplitudes rather than degrade entanglement. Selective attenuation improves interference contrast and state fidelity compared to uniform loss scenarios [**? ?** ].

### 7.2. Thermal Drift and Calibration

Thermal tuning of microring resonators leads to slow phase drift over time. Joint amplitude–phase control enables closed-loop calibration, where amplitude adjustments compensate for residual phase errors, resulting in superior long-term stability relative to phase-only architectures.

### 7.3. Robustness to Spectral Disorder

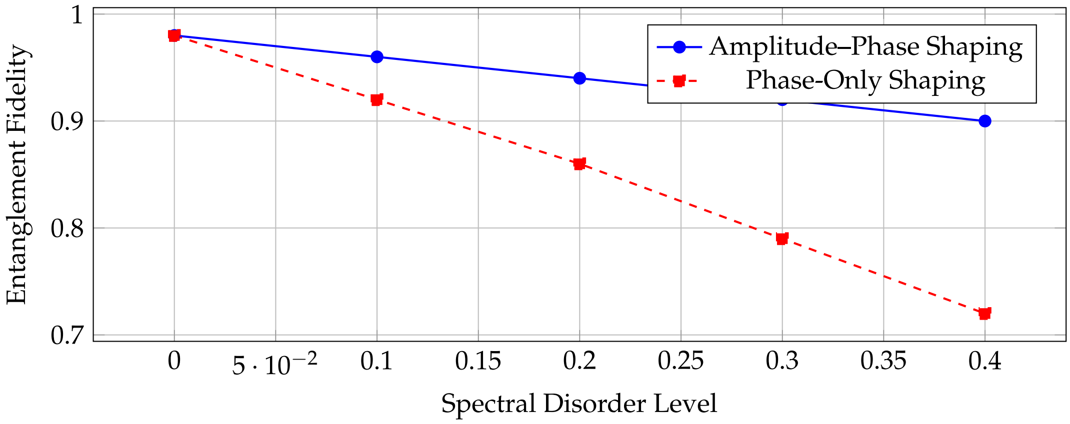

**Figure 4.** Entanglement fidelity versus spectral disorder. Amplitude–phase shaping significantly improves robustness against fabrication-induced spectral imperfections.

## 8. Conclusion

In this work, we have introduced and analyzed a fully reconfigurable *amplitude–phase on-chip biphoton pulse shaping framework* that overcomes fundamental limitations of phase-only spectral control in integrated quantum photonics. By enabling independent and programmable manipulation of both the amplitude and phase of individual frequency bins, the proposed approach provides complete access to the complex spectral transfer function of biphoton frequency combs. This capability represents a decisive step toward universal control of time–frequency entangled states on a scalable photonic platform. We demonstrated, through theoretical modeling and numerical analysis, that joint amplitude–phase shaping enables temporal waveforms that are strictly inaccessible under phase-only control. In particular, amplitude balancing suppresses temporal sidelobes, improves temporal localization, and enables asymmetric and application-specific biphoton wavepackets. These features are essential for interfacing entangled photons with narrowband quantum memories, cavities, and hybrid quantum systems, where precise temporal and spectral mode matching is required.

Beyond temporal waveform engineering, amplitude–phase control substantially enhances the effective dimensionality of frequency-bin entanglement. By compensating for nonuniform spectral amplitudes arising from fabrication variability and wavelength-dependent coupling, the proposed framework increases the usable Schmidt number and improves two-photon interference visibility. This improvement directly translates into higher information capacity, increased robustness to loss, and improved scalability for frequency-domain quantum communication and computation protocols. Importantly, we showed that amplitude–phase shaping also provides intrinsic robustness against realistic device imperfections. Joint control enables closed-loop calibration strategies that mitigate thermal drift, spectral disorder, and slow environmental fluctuations more effectively than phase-only architectures. Rather than introducing loss as a purely detrimental factor, selective amplitude attenuation can be exploited constructively to equalize spectral weights and stabilize entanglement properties over long operational timescales. These characteristics are particularly relevant for deployment in real-world quantum networks and compliance-critical environments where stability, repeatability, and explainability are essential.

In summary, fully reconfigurable amplitude–phase on-chip biphoton pulse shaping establishes a new paradigm for quantum state engineering in the frequency domain. By unifying temporal waveform synthesis, high-dimensional entanglement control, and robustness against practical imperfections within a single integrated framework, this work lays the foundation for next-generation quantum frequency processors and scalable quantum photonic technologies.

**Author Contributions:** All authors contributed equally to the writing of this paper. All authors read and approved the final manuscript.

**Conflicts of Interest:** "The authors declare no conflict of interest."

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