Development of a Fully Software-Controlled, Alignment-Free Loop-Delay Thermal Modulator for GC×GC

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Introduction

Loop-delay thermal modulation is a well-established approach for comprehensive two-dimensional gas chromatography (GC×GC) and inherently requires precise alignment of the modulation loop. In conventional designs, this alignment must be performed manually by the user, a process that is difficult, time-consuming, and often unreliable, as the modulation loop can shift during operation due to repeated hot-jet gas pulses, leading to misalignment and degraded modulation performance. This work addresses these limitations through a redesigned loop-delay modulator in which precise alignment is ensured intrinsically by the modulator geometry, eliminating user-dependent alignment while improving mechanical stability and operational robustness.

Key Improvements

- **Intrinsic loop alignment by geometry**, eliminating user-performed alignment
- **Mechanically secured loop holder**, preventing loop movement during hot-jet gas pulses
- **Easy loop winding**, simplifying installation and replacement
- **No moving mechanical parts**, improving robustness and reliability
- **Fully software-controlled modulation**, including hot-jet temperature, valve timing, modulation period, and cold-jet gas flow
- **Programmable cold-jet gas flow**, providing indirect control of modulation temperature
- **Programmable modulation period,** enabling flexible optimization for correcting peak wrap-around.
- **Independent of GC controls**, enabling standalone operation

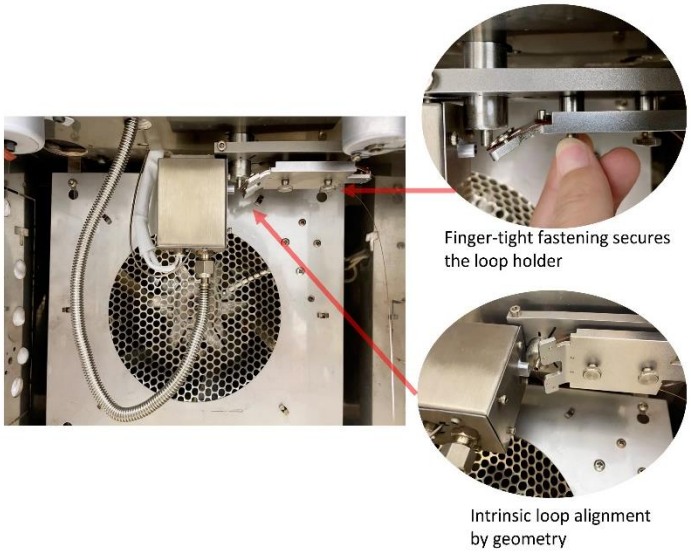

Figure 1. Alignment-free loop-delay modulator geometry. Intrinsic, geometry-enforced loop alignment eliminates user adjustment, while a mechanically secured loop holder prevents loop movement during hot-jet gas pulsing.

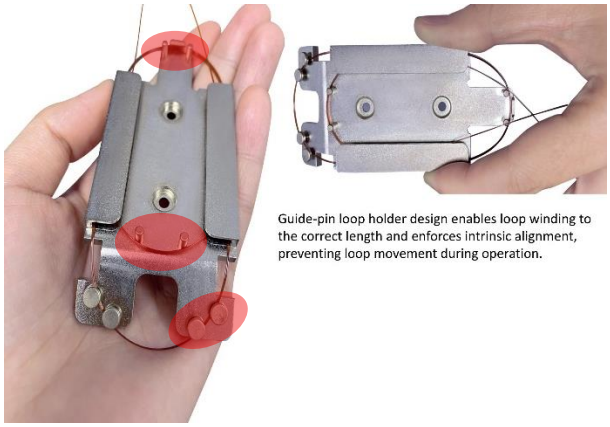

Figure 2. Guide-pin loop holder design. Integrated guide pins define the loop path and length during winding, enforcing intrinsic loop alignment and preventing loop movement during operation.

Tow Modulator Models

- **LN_2-Cooled Model:** Provides maximum cooling power for effective modulation of highly volatile C4+ compounds.

- **Electric Chiller Model:** Enables cryogen-free operation suitable for less-volatile C7+ compounds.

Both models employ the same alignment-free architecture and fully software-controlled operation.

Installation and Compatibility

Precise loop alignment is automatically achieved through the modulator's mechanical design. The loop remains fixed during operation and is not affected by hot-jet gas pulses. The compact, modular system is compatible with most commercial gas chromatographs and operates independently of GC control hardware and software.

Figure 3. Model L10 installed on an Agilent GC/QTOF system, demonstrating practical integration with a commercial GC–MS platform.

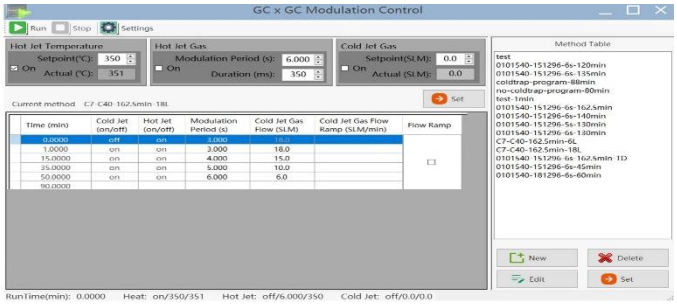

Figure 4. Control software interface for GC×GC modulation. The software provides independent control of hot and cold jet parameters and supports time-programmed modulation sequences through a user-defined method table.

Modulation Performance

Stable and efficient modulation was achieved for both highly volatile and less-volatile analytes. Representative GC×GC chromatograms demonstrate consistent modulation periods and effective peak focusing. Adjustment of cold-jet gas flow enables reproducible modulation behavior across different compound volatility ranges without direct temperature measurement.

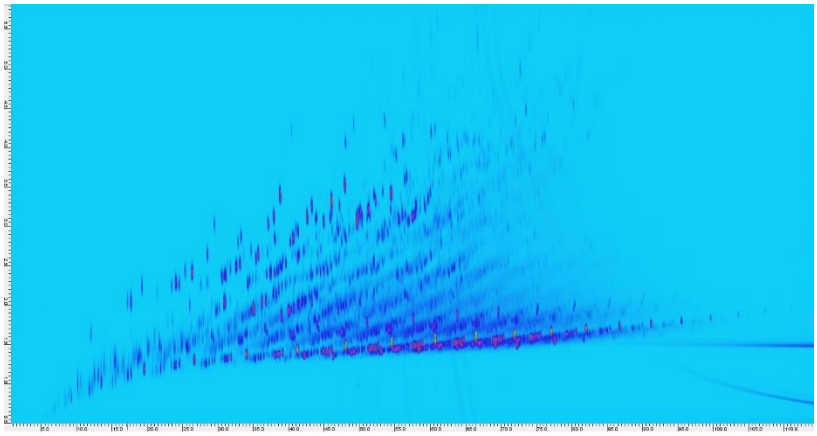

Figure 5. GC x GC chromatogram of a diesel sample acquired using the L10 thermal modulator on an Agilent 7890 GC with FID detector

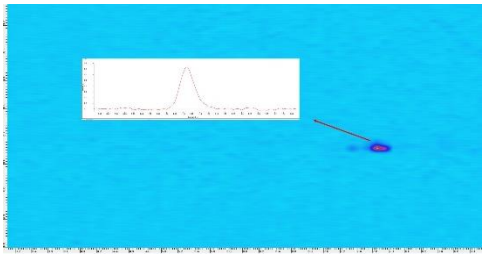

Figure 6. GC x GC chromatogram of a butane (C_4) sample acquired using the L10 thermal modulator on an Agilent 7890 GC with FID detector

Conclusions

A fully software-controlled, alignment-free loop-delay thermal modulator has been developed for GC×GC. By eliminating user-dependent alignment and mechanically stabilizing the modulation loop, the system significantly improves robustness and usability. Dual cooling options extend applicability across a wide volatility range, providing a practical modernization of traditional loop-delay modulation.

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