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Nonlinear Optics: KTP fiber-coupled phase modulators advance atom interferometry

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DAVID WALSH

Waveguide-based phase modulators that can handle high powers enable advances in inertia sensing, measurement of fundamental constants, laser frequency locking, and demonstrations of quantum phenomena.

In recent years, there has been growing need for suitable components to aid in atomic interferometry research and applications. To date, there has been limited access to suitable phase modulators operating in visible and near-infrared (NIR) wavelengths to correspond to atomic transitions of interest. This demand has driven the development of a new line of high-power fiber-coupled (HPFC) electro-optic phase modulators.

Atom interferometry has been called the Swiss Army Knife of atomic physics because of its numerous applications, which are based on coherently splitting and recombining atomic (de Broglie) waves.[1] Applications fall into four major categories: inertia sensing, measurement of fundamental constants, laser frequency locking, and demonstrations of quantum phenomena. In these applications, the extreme shortness of the de Broglie wavelength provides the basis for creating a next generation of precision measurement tools. For instance, an atom interferometer employed for inertial sensing can be used as an ultra-precise gravimeter (mapping earth's gravity) or inertial sensor, or to detect gravity waves and perform tests of general relativity in earth orbit.

Phase modulators are used in a wide range of atom interferometry instruments and experiments for spectral formatting a laser to interrogate atoms, locking lasers to atomic transitions, cooling atoms, and adding phase shifts. In general, the systems being built benefit from operating at higher optical powers, which increases the signal in the modulated optical sidebands of interest and consequently results in greater output signal from extremely weak de Broglie wave interactions.

Currently, most phase modulators on the market are made with lithium niobate (LN) in either bulk or waveguide-based configurations. While bulk LN phase modulators are capable of handling large input powers, the technology is limited by several shortcomings. Bulk phase modulators are difficult to produce in a fiber-coupled configuration, making them unattractive for applications requiring compactness and robustness. Additionally, the half-wave voltage (V_π) of bulk modulators is typically on the order of 100 V, making it challenging to obtain sufficient optical power in the sidebands, or to achieve broadband modulation greater than 1 GHz.

To avoid these issues with bulk modulators, many researchers turn to fiber-coupled modulators based on LN waveguides. This technology is well developed with low insertion loss, low V_π, and broad modulation bandwidth. Unfortunately, confining the optical power to a LN waveguide substantially increases the likelihood of photorefractive (PR) damage, limiting power handling in the visible and NIR wavelength range to just a few to tens of milliwatts. Heating of the LN waveguide can be done to slightly increase the damage threshold, but this causes lifetime degradation and adds unneeded complexity.

Recently, we have made advances in phase modulator technology, bringing high power-handling capability into a fiber-coupled, waveguide-based device with low V_π and a broad bandwidth. These HPFC phase modulators, available for wavelengths throughout the visible and NIR, are seeing increased interest from a number of diverse applications that benefit from operating at higher-input optical powers. These developments were made possible through Small Business Innovation Research (SBIR) grants from NASA and the Department of Defense for applications requiring high power handling and fiber coupling, which could not be satisfied by current commercially available products.

KTP waveguide-based modulator

To meet the need for increased power handling, HPFC phase modulators have been developed and introduced that conservatively have a 5–10X increase in power handling over traditional fiber-coupled phase modulators. To achieve this high power handling, waveguides in potassium titanyl phosphate (KTP) are used instead of traditional LN. KTP has a clear advantage over LN in terms of power handling PR damage.

In fact, it is believed that the power handling of the HPFC phase modulator is not limited by catastrophic damage in the KTP waveguide, but rather because of damage occurring at the fiber interfaces. The exact amount of power handling increase is specific to the operating wavelength of the phase modulator, and has yet to be thoroughly characterized. Just as with traditional FC phase modulators, there is a large amount of anecdotal evidence from customers about the power handling of the phase modulators.

Based on customer feedback, we can assert that, while traditional devices are limited to maximum operable powers in the 10–40 mW range at 780 nm, KTP-based HPFC phase modulators can be used safely at optical powers greater than 100 mW. In fact, users of the HPFC phase modulators at 780 nm have indicated operating in the range of 100–500 mW without degradation in performance (see Fig. 1).

FIGURE 1. An AdvR high power fiber-coupled (HPFC) phase modulator fabricated with KTP waveguides allows for significant power handling improvements over traditional phase modulators in LN. A HPFC phase modulator operating at 780 nm is capable of >100 mW input power with broadband modulation and low V_{π}.

To reduce the risk of optical damage at the fiber-waveguide interface, the HPFC phase modulator uses a proprietary no-epoxy-in-the-path coupling scheme, which avoids damages and optical losses that would have occurred in the epoxy. This coupling scheme enables insertion losses of <5 dB for 780 nm modulators, with even lower insertion loss options available.

Since the limitation in power handling for the HPFC phase modulators is believed to be because of damage at the fiber interfaces, a free-space version of the KTP phase modulator can be used to achieve >500 mW input power at 780 nm, while retaining low V_p and a broad modulation bandwidth. To date, there has not been any evidence from users that the HPFC phase modulator has failed because of PR damage in the KTP waveguide.

A significant portion of the demand for the HPFC phase modulator has been for operating wavelengths around 780 nm for use in rubidium sensing. These HPFC phase modulators at 780 nm have seen performance improvements because of more mature fabrication processing, but HPFC phase modulators operating at a variety of custom wavelengths in the visible and NIR have also been delivered.

This flexibility in wavelength allows customers to probe a range of atomic species of interest, including strontium, lithium, barium, iodine, cesium, calcium, and ytterbium, to name a few. Although HPFC phase modulators can be made for wavelengths beyond 1064 nm, power handling for LN-based modulators is typically sufficient in this region, and the increased power handling of KTP is not necessary.

While HPFC phase modulators are available in a broad range of visible and NIR wavelengths, further development needs to occur to optimize performance at these custom wavelengths. The KTP waveguides at wavelengths other than 780 nm are not currently guaranteed to be fabricated as single-mode. Although we believe that single-mode waveguides at these wavelengths will be developed with additional demand or developmental funding, a short-term solution has been realized by including a temperature control unit for each HPFC modulator at custom wavelengths to allow the output to be optimized and stabilized.

Sample applications

As noted, these phase modulators can be used in a variety of applications involving atomic interferometry. For instance, a primary application for HPFC phase modulators is in optical atomic clocks. Optical atomic clocks provide significant performance improvements over traditional atomic clocks based on interrogating an atom with a microwave signal. Using optical frequencies to interrogate an atom and serve as the ticks of the clock could eventually allow for performance improvements of 100 times over a conventional atomic clock.

The HPFC phase modulators have been used in various atomic clock configurations, including clocks operating on rubidium and cesium atoms. As these HPFC phase modulators grow more mature, they will become usable in space applications, including optical atomic clocks for GPS satellites, allowing for much more precise positioning.

HPFC phase modulators can find additional applications in the field of inertial navigation, which tracks the location of an object over any arbitrary path by measuring the acceleration and the rotation components of the object. Cold-atom accelerometers have proven to be ideal for inertial navigation since they offer excellent stability and precision for these local measurements over long time scales. This will provide a crucial alternative to GPS if a system fails or the signal is otherwise unavailable.

Recent approaches to probing the atomic resonances involved phase modulation of a single laser with an electro-optic phase modulation, thereby generating multiple sidebands in the desired frequency bands. The key advantage of this approach is the fast, reliable, and repeatable frequency selectivity and agility. This capability enables the application of cold atom interferometers in both fundamental and applied physics.

Related product capabilities

Developing these HPFC phase modulators in KTP waveguides allows for expanded product capability beyond just phase modulation. We have also developed a monolithic device based on a single KTP waveguide that offers both frequency conversion and phase modulation capability. These devices, known as Monolithic Second Harmonic Modulators (MSM), have a region with a standard electro-optic electrode for phase modulation of the beam, but in the same waveguide there is a periodic poled section to allow for quasi-phase matched frequency conversion.

One configuration of the MSM, for example, takes 1064 nm input light and frequency-converts it to 532 nm light, which is then phase-modulated before exiting through a PM fiber output. Another configuration allows for input at 1560 nm to be converted to modulated 780 nm light. This monolithic design eliminates the optical losses from using two discrete FC devices, and result in a more compact and easy-to-use system (see Fig. 2).

FIGURE 2. The AdvR Monolithic Second Harmonic Modulator (MSM) combines frequency conversion and phase modulation capability into a single fiber coupled KTP waveguide. The pictured unit takes a 1064 nm input signal and produces a modulated 532 nm output for use in many applications in atomic interferometry and laser locking.

The MSM has been developed through funding from SBIR grants from NASA, specifically for use in a frequency-stabilized seed source for a series of atmospheric lidar systems. In the frequency-stabilized seed laser, a 1064 nm fiber laser is input into the MSM to produce spectrally formatted 532 nm output. This signal is then used to lock to an absorption feature in an iodine vapor cell (see Fig. 3).

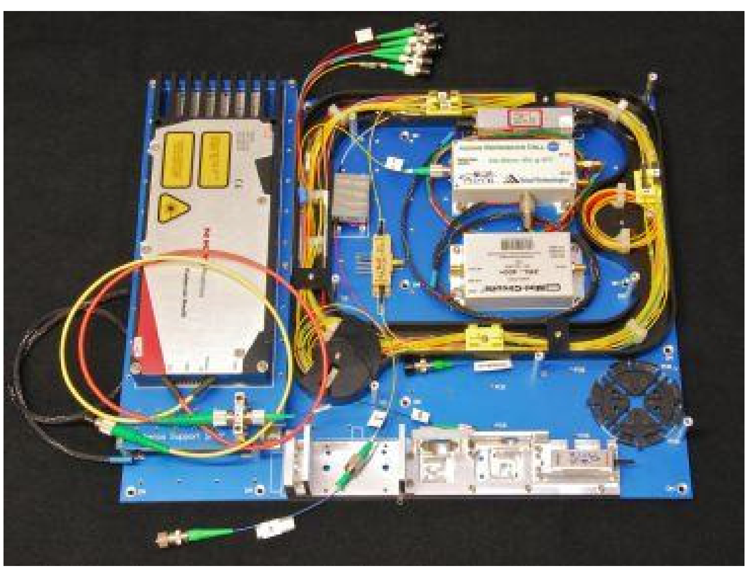

FIGURE 3. A laser frequency locking system utilizing the AdvR MSM has an input from a 1064 nm fiber laser that is spectrally formatted through frequency conversion and phase modulator in the

MSM to frequency lock the system to an iodine vapor reference cell.

Through these programs, the MSM has experienced continuing performance improvements. Most recently, the MSM has been undergoing intensive environmental testing, with the end goal of space qualification. This space qualification will enable the delivery of a stabilized seed laser for space-based lidar. The expansion of space-qualified technology to the HPFC phase modulator will improve space-based optical atomic clocks.

AdvR continues to look for developmental opportunities for these HPFC phase modulators. Future developments include optimizing devices for wavelengths other than 780 nm, eliminating the need for temperature control to maintain the insertion loss. Other potential improvements include extending the modulation bandwidth and continuing to ruggedize the packaging for real-world applications. As applications utilizing fiber-coupled phase modulators advance out of the laboratory setting, we expect HPFC phase modulators to play an important role.

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REFERENCE

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David Walsh is business development specialist at AdvR, Bozeman, MT; e-mail: dwalsh@advr-inc.com; www.advr-inc.com.