Problems of Acousto-Optic Tunable Filters for WDM Optical Switching

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Technology development toward the use of $LiNbO_3$-based acousto-optic tunable filters as WDM 2 × 2 cross-connect switches is reviewed. Recently, it was found that a fundamental behavior of multi-wavelength Bragg scattering critically affects the crosstalk performance of the acousto-optic tunable filter. We review several reported methods of overcoming the performance degradation. We will eventually ask whether the device is up to the task of WDM optical switching.

I. Introduction

Among the key components of transparent optical networks utilizing the wavelength-division-multiplexing (WDM) scheme, the WDM multiplexer appears to be the one that determines the complexity of the overall system more than anything else. According to functionality, WDM multiplexer designs can be classified into two kinds: The first is the fixed-channel router type such as etched-grating spectrographs[1] or dual-stars-with-arrayed-waveguides[2]. The second is the cross-connect type such as electro-optic tunable filters[3] and acousto-optic tunable filters (AOTF's). With wide tunability and multiple-channel switching capability of AOTF's, the $LiNbO_3$-based AOTF technology has been considered to be one of the leading technologies for WDM optical-switching applications. In this paper, a historical account of AOTF's is given with the underlying physics behind their operation characteristics. Problems of AOTF's to be used as WDM optical cross-connect switches are discussed along with a series of ingenious solutions. Finally, we will consider whether the AOTF technology is really useful for this usage.

II. Background as a WDM Switch

From the beginning of its invention[4, 5] in 1969, the usefulness of the AOTF as a narrow-band optical filter was especially noted. The basic principle of operation is based on a well-known mechanism called codirectional Bragg-scattering in a periodic structure created dynamically by the excitation of the acoustic wave in a bi-modal structure, e.g., polarization-conversion of tuned wavelength in naturally birefringent piezoelectric material such as $CaMoO_4$ and $LiNbO_3$[6].

The most notable advantage of the device is its electronic tunability over a wide band of wavelengths. One can change the RF frequency so that the corresponding optical frequency of the interacting light is chosen at will. The amplitude of the acoustic wave can also be adjusted by RF amplitude tuning so that a mode conversion from one mode to another is complete for the tuned wavelength.

For optical-information processing applications, various improvements were made by using a $LiNbO_3$ substrate[7] with surface-acoustic waves (SAW's) instead of $CaMoO_4$ with bulk acoustic waves, by confining both optical waves and acoustic waves in a small cross-sectional area guiding both waves[8], and by using the X-cut $LiNbO_3$ substrate instead of the Z-cut substrate[9].

Another attraction of the AOTF is its multiple-channel filtering capability among various types of wavelength-selective filters. In fact, the device began to draw great attention when Cheung[10] proposed the use of AOTF's as a 2 × 2 cross-connect switch units in a multiple-channel wavelength-selective space-division switch fabric. Reliable WDM 2 × 2 cross-connect switches in the design of optical networks provides enormous flexibility[11, 12] over other WDM mux-demuxes such as WDM fixed-channel routers. Initial demonstration of the proposed functionality was reported in Ref. [13] with reasonable performance. No other device seemed to provide this level of flexibility than AOTF's[14] in terms of scalability, frequency-reuse, reconfigurability, multi-hop, etc. A brief comparison of various WDM optical switches can be found in Ref. [12]. The only fundamental drawback of the device was thought to be relatively slow switching speed due to the slow transit time of the acoustic waves in the order of 10 μs.

However, it was immediately realized that a great amount of technology development would be necessary to utilize AOTF's in practical WDM networks as WDM 2 × 2 cross-connect switches. Problems such as polarization dependency[15] and differential optical-frequency shift due to Doppler effect[16, 17] were trivially solved by adopting a so-called polarization-diversified structure as illustrated schematically in Fig. 1. The most critical problem

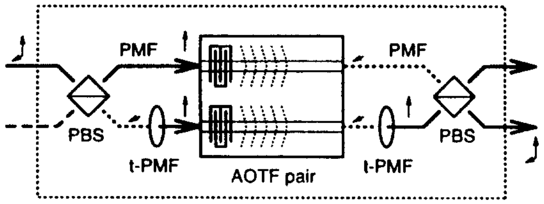


Fig. 1. A 2×2 cross-connect switch unit made of a polarization-diversified acousto-optic tunable filter (PD-AOTF). PBS: (Glan–Thompson) polarization beam splitter. PMF: polarization-maintaining fiber. t-PMF: 90°-twisted PMF for polarization rotation.

of AOTF switches to be utilized in WDM optical networks is the crosstalk between channels. The most obvious cause of the crosstalk was fabrication inaccuracy which creates large, seemingly unpredictable, asymmetric sidelobes[18, 19, 20]. Early in the development of AOTF's for WDM optical switching, it was thought that the system specification would be met if the Ti-LiNbO$_3$ fabrication process would be sufficiently refined.

III. Redesign of Acousto-Optic Interaction Profile

Along with the advances in fabrication-process refinements, a schematic redesign of the acousto-optic interaction (AOI) profile of the filter was considered necessary to reduce the sidelobe level of -14.5 dB of the basic rectangular AOI profile shown in Fig. 2(a). Apodization of the perturbation profile was a well-known technique in reducing the sidelobe levels in both codirectional and contradirectional Bragg filters[21]. Among various methods of achieving the apodized AOI profiles, a directional-SAW-coupler design with dual SAW-guides on a LiNbO$_3$ substrate[22] yielding a half-period sine profile of Fig. 2(b) was quite effective.

In parallel with all these developments in the device-technology side, the work on actual use of AOTF's and electro-optic tunable filters in systems experiments revealed that the crosstalk due to insufficient rejection at the filter band is far more critical than the crosstalk due to sidelobes. This can be understood as follows: Due to the intrinsic characteristics of the narrow, peaked passbands of an untreated codirectional Bragg filter, the drifting or inherently inaccurate wavelengths of laser sources in a WDM system creates substantially greater crosstalk in the bar port than the sidelobe levels in the cross port of a 2×2 switch.

This argument called for a near-ideal spectral characteristic from a codirectional Bragg filter. That is, a codirectional Bragg filter should have a range of near-unity response within a flattened passband. It was found that this passband engineering could be realized by a clever redesign of the AOI profile[23] according to the rigorous inverse-scattering method[24]. That is, a profile as shown in Fig. 2(c), which is obtained by a synthetic approach of inverse-scattering method, can give a spectral curve which has both negligible sidelobes and a nicely flattened passband[25].

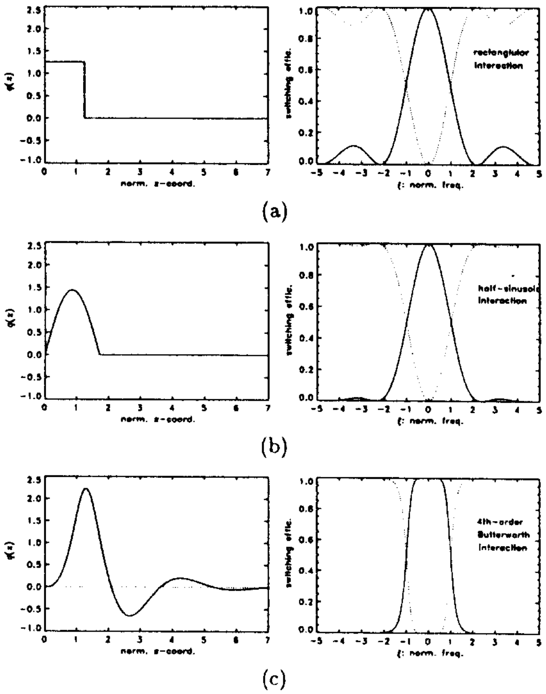
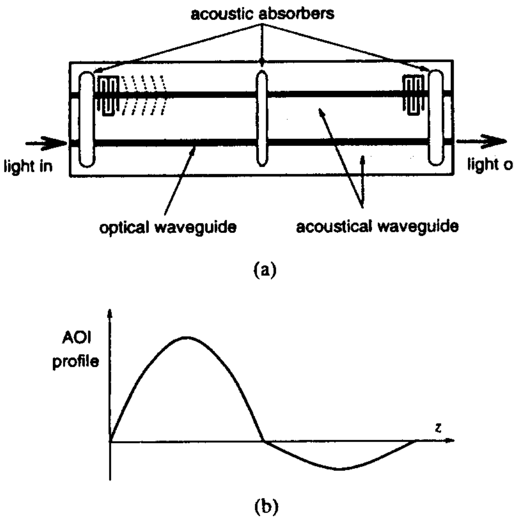


Fig. 2. Three acousto-optic interaction profiles in the left and their respective switching efficiency spectra in the right. Solid and dotted spectral curves represent the power efficiencies of the band-pass and band-reject ports, respectively. (a) For the rectangular-function profile. (b) For the half-period sinusoid profile. (c) For the fourth-order Butterworth profile. Note that all three profiles are normalized to give 1/2 efficiency at normalized detuned frequency $\xi = \pm 1$.

Two aspects of the solution profile in Fig. 2(c) are notable. First, the profile is alternating between positive and negative phases. Second, the profile should turn on smoothly without a sharp turn. Understanding of the basic coupled-wave mechanism gave an initial idea of realizing this special profile experimentally[23]. That is, the phase-polarity change is automatic in the directional SAW-guide coupler, and the amplitude of the AOI profile can be controlled by the gap distance of the tapered directional coupler and a distributed SAW attenuator. A version[26] approximating the ideal solution profile was eventually made and was reported to have a noticeably flattened passband while keeping sidelobes reduced. It used only two sections of opposite-phase AOI half-period sine profiles of different magnitudes by applying a SAW attenuator in the middle where the profile has a node as shown in Fig. 3.



(a)

(b)

Fig. 3. (a) A simple passband-flattened AOTF for counter-propagating-surface-acoustic-waves configuration and (b) the acousto-optic interaction (AOI) profile with the surface-acoustic-wave (SAW) for a single channel. In multi-channel coswitching, both SAW transducers are used for counter-propagating-SAW configuration in an alternate fashion.

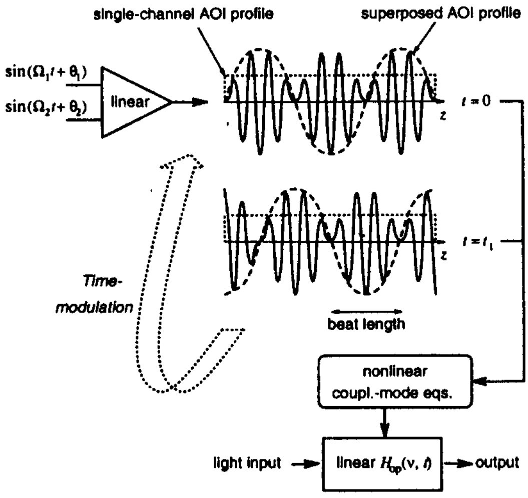


Fig. 4. Schematic illustration showing time-dependency and nonlinear effect of AOTF's driven by multiple RF's. Two SAW's of frequencies Ω_1 and Ω_2 with two respective initial phases θ_1 and θ_2 are transformed to an optical-filter function $H_{op}(\nu, t)$ by the coupled-mode equations.

IV. Multi-Channel Coswitching

The crosstalk characterization of multi-channel operation was reported in Refs. [13, 27, 28], in which degradation of crosstalk performances were observed at nominal wavelengths when multiple channels were switched simultaneously. In a time-averaged spectral measurement during a recent WDM optical-network test-bed experiment[29] with AOTF's, G.-K. Chang and M. Z. Iqbal[30] first discovered rather unwelcome shift of the passbands when closely-located multiple wavelength channels were switched simultaneously. The phenomena were analyzed in detail and the other aspects of the temporal modulation were predicted in a recent paper[31]. The essence of the analysis is described below.

When multiple SAW's are launched for the corresponding channels, a simple rectangle-shaped AOI profile, for instance, will be modulated as in Fig. 4. The newly created Bragg scatterer on $LiNbO_3$ will be a pattern that is modulated in both space and time from multiple RF inputs under the linear superposition principle. Note however that a near-complete mode conversion between TE and TM modes is not linear. The transformation from the modulated SAW profile to an optical-filter function, the analysis of which can be interpreted as the solution procedure to the coupled-mode equations, is nonlinear. Thus nonlinear effects such as passband shifts can happen when the channels are sufficiently close. In addition to the passband shifts, the modulation model suggests that the beat pattern will move with the SAW group velocity. Therefore the light, passing through the AOI region, sees one of the many variations of a moving AOI profile at different instances. *The whole response then fluctuates* at the difference frequencies of input RF's, e.g., ~ 500 kHz, and their harmonics due to the nonlinear effect.

A simulation study was performed[30] suggesting that the nonideal rejection at the passband critically degrades. The implication of this phenomena is rather profound. That is, it could be fundamentally difficult to effectively switch multiple channels with one physical unit of an AOTF-based optical switch.

The effect of multi-channel coswitching can be significantly reduced by a clever scheme of counter-propagating SAW's for the neighboring channels in the reduced-sine profile of Fig. 3(b)[32]. Suppose that there are four channels in a WDM network system. The switching control of the first and third channels is done through the SAW's launched by the left-hand-side transducer in Fig. 3(a), while that of the second and fourth channels is done through the SAW's launched by the right-hand-side transducer. Then the overlap of the AOI profiles for the adjacent channels are significantly reduced from the scheme in which SAW's for all channels are launched by one transducer. Theory[30] and experiments[32] showed that the improvement is significant, e.g., around 5 dB for a moderate channel spacing of 4 nm with the total AOI length of 35 mm.

With all these design improvements, the optimum design of the AOI profile[31] should consider the following factors.

1. Number of alternating-phase sections approximating the near-ideal AOI profile found by the inverse-scattering method. More than two sections may occupy too great estate on the $LiNbO_3$ substrate for a

given 3-dB bandwidth.

2. The physical length will determine the switching speed and the 3-dB bandwidth of the single-channel filter for a given profile design.
3. The tapered on-set of the AOI profile will reduce the sidelobe levels significantly, but will occupy space.
4. The pass-through factor of the partial absorber. Larger pass-through factor tends to widen the flattened range of passbands, while worsening the rejection level in the passband in the multi-channel coswitching condition.

In fact, it is by now well-known that a future WDM wavelengths will utilize the wavelengths from 1540 nm to 1560 nm due to the limited flat-gain spectral range of commercial Er-doped fiber amplifiers. To utilize as many as eight or nine channels in this range, the channel distance must be set at around 2 nm. Accordingly, the bandwidth should be at least as narrow as or even narrower than the channel distance. One should realize that the physical length of AOI profile is inversely proportional to the 3-dB bandwidth. Also, the effect of multichannel coswitching depends on the single-channel switching bandwidth and the channel distance. The length of two-section, passband-flattened AOTF with the AOI profile of Fig. 3(a) should be at least greater than 45 mm with the worst-case rejection crosstalk of −12 dB. One should understand that the excessive length requirement ultimately comes from insufficient birefringence of $LiNbO_3$ material.

V. Dilation

It should be noted that the dilation of switch fabric is generally considered necessary to achieve the desired crosstalk level in most, maybe not all, optical switching network designs[33]. The dilation became even more important when a simulated in-band crosstalk study[34] for a transparent optical network was recently published suggesting that much lower crosstalk (≤ -35 dB) from a network element than previously thought levels is required for robust operation of a large-size transparent optical network. In a cross-connect configuration, it can be understood as follows: The residual signal power in the unintended port of the active 2 × 2 switch leaks into the network if unterminated. This crosstalk noise components may accumulate in the transparent optical network, and they interfere coherently at wrong terminal locations. This suggests that worst-case crosstalk which determines the ultimate crosstalk performance is much worse than incoherent accumulation of stray-signal power.

The importance of dilation for AOTF cross-connect switches increased with the finding of the fundamental limitation of AOTF's for WDM optical switching. One should note that there are two kinds of crosstalk — sidelobe crosstalk and rejection crosstalk, and that they are not equal. With a narrow-band switch such as an AOTF, the imbalance between these two kinds of crosstalk are especially great enough to consider asymmetrization of dilation[17]. For a dilated (two-stage) 2 × 2 switch, there are three possible implementations as shown schematically in Fig. 5. All of these dilation schemes improve the crosstalk performance of a dilated switch fabric by dumping all the first-order crosstalk noise into unused ports while leaving only the second or higher-order crosstalk noise in the output ports. Careful analysis shows that only the architecture of Fig. 5(c) balances out the unequal crosstalk levels between the sidelobe-related crosstalk and the rejection-related crosstalk. Also, only this architecture was found to be intrinsically immune to the noise-cycling problem[35] when a ring is formed along any optically transparent signal paths. The third advantage of the scheme is that the width of the switching passband is also balanced. A simulation study has shown that the crosstalk improvement by employing this special asymmetrization scheme is around 10 dB in the case of AOTF-based WDM optical switches with the ultimate worst-case, two-stage crosstalk performance of around −30 dB[17].

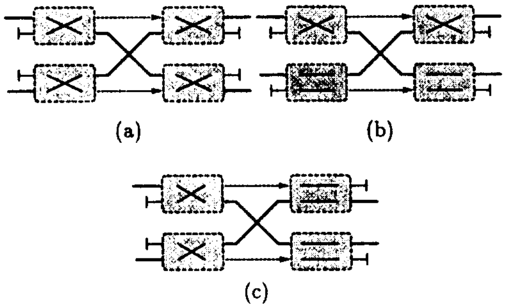


Fig. 5. Three two-stage 2 × 2 switches in overall cross-state. (a) Symmetric dilation. (b) Vertically asymmetric dilation. (c) Horizontally asymmetric dilation.

The basic idea of asymmetric dilation is found to be systematically extendable to larger-size cross-connect architectures[17] such as a fully dilated 4 × 4 WDM cross-connect as shown in Fig. 6.

The simulation study in Ref. [17] presumes that the lasers have well-tuned nominal wavelengths in a WDM network. In reality, it is highly probable that the wavelengths will drift and stray within the acceptable range of spectrum centered at each of several nominal wavelengths that will be selected by standard organizations. The rejection performance will then suffer even greatly, and the improvement from asymmetric dilation will be even greater than the result from preliminary simulation..

A second architectural approach to reducing crosstalk is the use of "wavelength dilation," which, in fact, was originally proposed as a way of improving AOTF performance[36]. For an overall $N \times N$ cross-connect routing, it uses 2 N passive wavelength splitters such as Mach–Zehnder interferometric devices so that, using N input wavelength splitters, even channels are directed to one $N \times N$ cross-connect switch fabric and odd channels are directed to another $N \times N$ cross-connect switch fabric. After the conventional cross-connect routing, one must combine

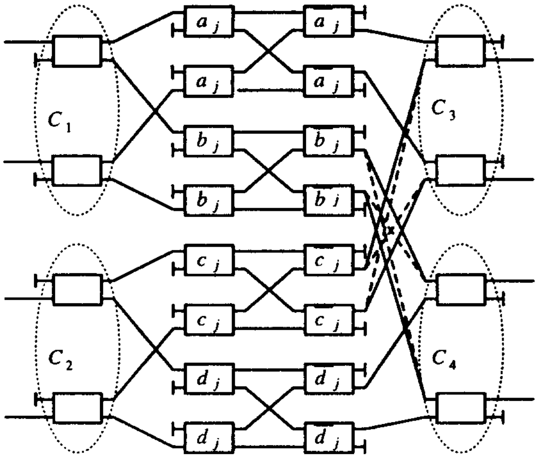


Fig. 6. A strictly non-blocking, asymmetrically-dilated 4 × 4 cross-connect switch. Letters a_j, b_j, c_j, and d_j represent the four independent logical variables of driving the jth channel, while $\overline{a_j}$ represents the logical 'not' of a_j, and so forth.

the two wavelength-dilated routing paths into N ports. Overall performance of the architecture depends heavily on the performance of the passive wavelength splitters which needs to have a comb-like response, desirably that of a square-pulse train. Admittedly the overall architecture becomes overly complicated, and practicality of this technique should be considered seriously.

VI. Conclusion

It is unfortunate that the crosstalk specification of network elements has become far tighter than previously thought as one understands the physical implication of transparent optical networks. The conventional LiNbO3-based AOTF is found to have a limitation as a WDM 2 × 2 cross-connect switch. However, it may find a good practical use as a drop-add multiplexer where a multiple-channel switching capability is not needed. It is possible to use the device in instrumentation to analyze light spectrum in an optical network. It is even possible to use it to multiplex and demultiplex between 1.3 μm and 1.5 μm light in small-scale WDM systems with a switching speed faster than any mechanical switching speed.

A different version of an AOTF using a bi-modal optical fiber was recently proposed by a research group in Korea[37]. Instead of polarization-mode conversion, it uses the mode conversion between LP_{01} and LP_{11} modes. If it is intended to be used as a multiple-channel coswitching device with only one acoustic-wave transducer, the device will suffer from the same problem of nonlinear superposition of filtered responses. However, one can consider cascading of switching units for multiple channels.

There are other types of low-technology WDM filters such as mechanically-moving multi-layer thin-film filters. Some new technology is also emerging such as dual grating-based liquid-crystal 2 × 2 switch[38]. Even though they are slow, the crosstalk performance of such devices is superior to that of an AOTF in general. One should be keen to some very new technology for the real winner of WDM optical switch technology.

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