Simple planar Bragg grating devices for photonic Hilbert transformer

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Abstract. In this work the theoretical design and experimental realisation of a photonic Hilbert transformer is investigated. Planar Bragg gratings are proposed as a route to realise photonic Hilbert transformers in terms of a finite bandwidth and temporal impulse response. With proper grating apodisation and \( \pi \)-phase shift, the Bragg grating will display the spectral features expected from a Hilbert transformer. The unique features of Direct UV grating writing technology are used to fabricate the proposed device in silica-on-silicon

1. Introduction
Hilbert transformers are important devices widely used in communication, information processing and signal analysis in the electronic domain [1]. A photonic Hilbert transformer (PHT) can be employed in a similar range of applications, which would enable the direct processing of optical signals at high speeds as well as operation bandwidths far beyond current electronic technologies.

Based on discrete free space photonic components, PHTs have been realised, e.g., multi-tap fiber-optics transversal filters and sampled fiber Bragg gratings [2–5]. Recently, single phase-shifted Fiber Bragg gratings (FBGs) with proper apodisation profile for PHT have also been presented [6,7]. However, most are about theoretical simulation or with multiple components; to date no simple PHT device has been experimentally reported. Here we present initial efforts to fabricate an integrated PHT, which provides a route to realise compact optical modules for applications such as single sideband (SSB) modulation.

In this paper, we present initial efforts to practically demonstrate a PHT using an appropriate apodised planar Bragg grating with a \( \pi \)-phase shift in the grating section. The Bragg grating is fabricated by direct UV grating writing (DGW) technology on a silica-on-silicon platform [8]. In the future, the integrated nature of planar geometry will allow these devices to be combined with other functions, such as liquid crystals and thermal tuning elements to generate reconfigurable devices.

2. Operation principle
The ideal frequency response of a Hilbert transform \( \tilde{H}(\omega) \) is defined as [1]:

\[
\tilde{H}(\omega) = \begin{cases} 
-i, & \omega > 0 \\
i, & \omega \leq 0
\end{cases}
\]

(1)

where \( \omega \) is the baseband frequency. Figure 1 shows the ideal frequency response of a Hilbert transform with a constant amplitude and a \( \pi \)-phase shift at \( \omega=0 \).
Physically realisable response: $|H(\omega)|= 1$

Phase response: $\theta(\omega) = -(\pi/2)\text{sgn}(\omega)$

Figure 1. (a) PHT amplitude responses, (b) PHT phase responses (ideal in solid lines, physically realisable in dashed lines).

In practice a physically realisable device would have a limited frequency bandwidth and temporal impulse response, also shown in Figure 1. To realise such spectral features, the ideal practical Bragg device could incorporate an apodisation profile with the necessary $\pi$-phase shift, similar to the FBG derived from the first-order Born approximation (weak-coupling FBG) in reference [6]. The grating apodisation profile is given by the expression below:

$$\Delta n(z) \propto \sin^2\left(\frac{\pi n_{\text{eff}} \Delta f (z-z_0) / c}{(z-z_0)}\right)$$

In equation (2), $z$ is the grating position along the waveguide with $0 \leq z \leq L$, while $L$ is the total grating length, $n_{\text{eff}}$ is the effective refractive index of the planar Bragg grating, $\Delta f$ is the operating bandwidth, $z_0$ is the zero-crossing point in the apodisation function and $c$ is the light speed in vacuum. $z_0$ is set to the centre of the grating length for simplicity. For the designed Bragg wavelength $\lambda_B$, the grating period is $\Lambda = \lambda_B / 2n_{\text{eff}}$.

Figure 2 shows the shape of the apodisation profile for the proposed grating. As anticipated, the resulting grating apodisation profile requires a single $\pi$-phase shift along the grating length. The zero-to-zero width of the side lobes $\Delta z$ in the apodisation profile is directly related to the full operation spectral bandwidth $\Delta f$ of the PHT, where $\Delta z = c / n_{\text{eff}} \Delta f$. Negative $\Delta n$ relates to a $\pi$-phase shift in the apodisation profile.

3. Fabrication and experimental results

Figure 3 illustrates the direct UV grating writing (DGW) technology used to fabricate the proposed planar Bragg gratings [8]. This method involves focusing two crossed laser beams ($\lambda=244\text{nm}$) into the photosensitive core of a planar sample. UV irradiation increases the refractive index in this layer. Precise translation of the sample and modulation of the laser intensity both defines the channel waveguide and simultaneously the creation of the grating structures [8]. This spot size is approximately $6\mu\text{m}$ in diameter, providing the unique ability over traditional FBG to manipulate the grating structures at the micron level. This ability allows precise engineering of the amplitude and phase responses of the proposed gratings for PHTs.
The apodisation profile shown in equation 2 was used to fabricate a Bragg grating for application as a PHT. Modeling was used to ensure that grating parameters produced an apodisation profile which was truncated at points where $\Delta n = 0$. Thereby reduce rapid changes in the propagation constant of the waveguide and hence additional spectral features.

Figure 4(a) shows the reflectivity of a Bragg grating that contained a $\pi$-phase shift and apodisation profile using the following parameters, $L= 15$mm, $\Lambda=535.467$nm, $n_{\text{eff}}= 1.4478$, $\Delta n= 0.0003$, and $\Delta f= 140$GHz. The reflectivity spectrum shows a rectangular spectral response, the result of the apodisation and a strong dip (~-20 dB) characteristic of the $\pi$-phase shift.

Figure 4(b) shows the relative group delay of the reflected signal. It demonstrates a comparatively flat group delay within the operating bandwidth with an abrupt change in the centre, a consequence of the phase shift. Both reflectivity and relative group delay were measured using the modulation phase-shift method. The poor dynamic range of the reflectivity measurement is a result of the limited sensitivity of the high bandwidth photoreceiver. According to Figure 4(a), the Bragg grating operates at 1550.5 nm and has a bandwidth of ~1.2nm (~150GHz) bandwidth, both values agreeing with the target parameters. It should be noted that these planar waveguide devices are birefringent and are therefore polarization dependent.

Direct phase measurement of the Bragg grating will be required to qualify that this device performs as a Photonic Hilbert Transformer. However the asymmetric features on the reflectivity peak are characteristic of a small error in the $\pi$-phase shift. Modeling has shown that a ~5% error in the magnitude of the $\pi$-phase shift produces similar features as shown in figure 4(a). This analysis shows that further work is required to reduce such fabrication errors which are likely to be a result the stability of the laser source and nonuniformity of the planar sample. However this analysis also shows that the phase shift is within 5% of the target $\pi$-phase shift.

**Figure 3.** Illustration of the fabrication process with direct UV grating writing in silica-on-silicon.

**Figure 4.** The measured reflection spectrum (a) and relative group delay (b) of the single $\pi$ phase-shifted planar Bragg grating with the apodisation profile for Hilbert transforms.
4. Conclusions
We have presented data demonstrating \(\pi\)-phase shifted Bragg gratings with an apodisation profile, for applications as a PHT. The spectral results agree with the target parameters and suggest that the \(\pi\)-phase shift is correct to within 5\%. Future work will investigate the phase response of the Bragg grating to qualify the device performance for operation as a Photonic Hilbert Transformer. The planar integrated format also offers a route to stable operation and allows high density integration.

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