Building an ideal microwave photonic bandstop filter

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A new class of microwave filters with unequaled performance, based on a tiny on-chip resonator combined with light-sound interaction, enable coherent control over light carrying microwave information.

Radio-frequency (RF) filtering, an important signal-processing function in wireless communications, is used to separate an information signal from unwanted noise and interference. Traditionally, sharp and high-extinction electronic filters operating at a fixed central frequency are used to remove interference. This approach severely limits the flexibility of the system, however. In modern software-defined radios, where wireless systems are expected to share the RF spectrum, high-quality filters that are tunable over a wide frequency range are desired. These filters must meet a number of requirements, including wide-frequency tuning, high resolution, high suppression, and low insertion loss. Achieving all of these requirements with electronic filters is extremely difficult, however, as a result of their performance degradation when tuned over a large bandwidth.

Microwave photonic (MWP) filters, a technology that uses a tunable optical filter to select RF signals that are modulated onto an optical carrier, represent an alternative approach that can readily achieve frequency tuning of tens of gigahertz with no performance loss. For one, their resolution is on the order of a few GHz, which is at least two orders of magnitude lower than that required for RF signal processing. Additionally, they suffer from trade-offs between resolution and filter suppression. Because of the losses that are associated with optical modulation and detection processes, MWP filters also suffer from a high insertion loss that can be prohibitive for real-world applications.

We devised three steps to systematically remove the performance-limiting factors of regular bandstop filters (as illustrated in Figure 1). First, we used a high-resolution optical filter based on stimulated Brillouin scattering (SBS), i.e., a strong optical nonlinear effect that results from the interactions of light and high-frequency acoustic waves. Observed as an optical gain resonance with a spectral width in the MHz range, SBS gives a resolution improvement of nearly three orders of magnitude compared to other optical filters. Crucially, we can induce and control SBS in chip-scale optical waveguides, as opposed to long-length optical fiber (where it has been traditionally demonstrated). Therefore, for the first time, optical filters with RF resolution and precision can be integrated in a photonic circuit.

As in many optical bandstop filters, however, the limiting compromise between spectral resolution and stopband suppression persists in SBS. We therefore focused on decoupling these two properties in the second step of our optimization scheme by employing a novel cancellation filter topology. For this purpose, we devised a precise control scheme to generate a pair of RF sidebands with opposite phase and unequal amplitudes, prior
to the SBS filtering, that were used to equalize the amplitude in a selected portion of the spectrum.\textsuperscript{13} After photodetection, the mixing products of these sidebands and the optical carrier cancel to varying degrees, depending on how well the amplitude balance is achieved. As a result of a perfect cancellation, the spectral region filtered with SBS forms a stopband with an infinite attenuation. At partial cancellation, the rest of the spectrum will form an attenuated passband. Despite a host of groundbreaking results, including a record on-chip filter performance,\textsuperscript{13} this cancellation technique suffers from an elevated insertion loss due to the passband attenuation. The impact of this additional loss will lead to an elevated noise figure and much-reduced dynamic range, thereby limiting the usability of the filter.

We recently demonstrated a bandstop filter that overcomes these issues and features no passband loss while retaining all the strengths of a cancellation filter, thereby realizing a nearly ideal filter.\textsuperscript{5} In this inventive technique, unbalanced and phase-inverted sideband pairs are synthesized only at the intended spectral region of the stopband (e.g., in a spectral band around 7GHz, as shown in Figure 2). In contrast, in-phase equal-amplitude sidebands are created for the rest of the spectrum, resulting in strong transmission in the passband. We carried out this sideband tailoring not at the modulator, but instead by using an integrated ring resonator in an overcoupled state, which exhibits 180° phase inversion at the center of its resonance: see Figure 2(a). We then applied a tailored SBS gain response at the output of the ring to compensate for its amplitude response: see Figure 2(b). With this technique, we are able to demonstrate tunable-width and high-extinction notch and square bandstop filters with an optimized insertion loss and GHz-frequency tuning for the first time: see Figure 2(c).

In summary, we have developed a novel approach for realizing a lossless MWP bandstop filter with all-optimized quality by combining optical responses from an overcoupled ring resonator and a precisely tailored SBS gain. By combining this result with our recent breakthrough\textsuperscript{17} (i.e., integrating an on-chip SBS element in a silicon chip), we now aim to demonstrate the full integration of this lossless filter in a photonic chip (see Figure 3).

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**Figure 2.** Operation principle of our ideal MWP bandstop filter. (a) Overcoupled ring-resonator response for sideband phase inversion. (b) Tailored SBS response for amplitude compensation of the ring response. (c) Experimental result of the square bandstop filter obtained using the new technique.\textsuperscript{5}

**Figure 3.** Artist’s impression of the all-integrated on-chip implementation of our ideal bandstop filter. As an example, the optical modulator and ring resonator can be integrated in silicon while the on-chip SBS medium can be heterogeneously integrated in chalcogenide glass.
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References