Abstract—Spectrometers are widely used for characterizing materials. Recently, filter-based spectrometers have been proposed to lower the manufacturing cost by replacing optical components with low-cost wavelength-selective filters, but at the expense of possibly lowered signal quality. We present compressive spectrometers which, based on the compressive sensing principle, are able to recover signal with improved quality from measurements acquired by a relatively small number of low-cost filters. We achieve high quality recovery by leveraging the fact that spectrometer measurements typically follow the shape of a smooth curve with a few spikes. We validate our method with real-world measurements, and release our dataset to facilitate future research.

I. INTRODUCTION

Spectral analysis is a well-established technique used in physics, chemistry, and biology. It provides detailed information related to the chemical bonds of the molecule, and thus can identify the compositions of the sample and their concentrations [1] [2].

Conventional optics-based spectrometers are expensive due to high-cost optics components and their large physical footprints. Recently, miniature filter-based spectrometers [3] [4] have emerged to provide cost and size advantages over optics-based spectrometers. Instead of using dispersers, the new approach employs a bank of wavelength-selective filters to detect the corresponding spectrum. However, these miniature spectrometers usually cannot resolve the spectrum at a fine-gain level due to the difficulty of manufacturing filters with small leaks, resulting in lower signal quality. Additionally, many filters are needed in order to capture a large set of target wavelengths.

To overcome the drawbacks of filter-based methods [5], our proposed compressive spectrometers use a small number of filters to capture information from multiple wavelengths at the same time. Based on sparse signal recovery principles in compressive sensing [6], we present a high-quality signal reconstruction method that exploits the fact that spectrum signal normally exhibits itself as a smooth curve with a few spikes.

II. HYBRID MODEL OF SMOOTHNESS AND SPARSITY

Spectrum signal tend to be a smooth curve with a few spikes of varying magnitudes. This is the result of several contributing factors throughout the sensing process, as illustrated in Figure 1. We propose a signal model that treats the signal $x$ as the composition of a sparse component and a smooth one: $x = v + \Psi z$ where $v$ is smooth, $\Psi$ is a sparsifying basis and $z$ is sparse. The measurements $y$ is defined as $y = \Phi x$ where $\Phi$ is the sensing matrix.

The sparsity and smoothness assumption manifests as separate regularization terms in the optimization problem for signal reconstruction:

$$\arg\min_{v,z} \|y - \Phi(v + \Psi z)\|_2^2 + \lambda_1 \|z\|_1 + \lambda_2 \|Av\|_2^2$$

where $A$ is a bidiagonal $(1,-1)$ matrix such that $Av$ captures gradients in adjacent components of $v$. The choice of using $\ell_2$ norm rather than $\ell_1$ norm for $Av$ reflects the fact that $v$ is more likely to have many small changes instead of few large ones. Note that (1) is convex and can be solved efficiently with gradient descent methods [7].

III. EVALUATION

To evaluate our method, we collected a dataset [8] that includes compressive spectrometer characteristics (see Figure 4) and spectrum of common plastic objects in the real world (see Table I). Note that our dataset is much more realistic compared to signals used in prior spectrometer signal recovery experiments, which only focused on simple Gaussian-like responses from simple LED sources.

We compare our hybrid method with state-of-the-art methods: conventional sparsity-based recovery method using a sparse model in $l_1$ [3] and the Tikhonov regularization method in $l_2$ (based on smoothness assumption) [4]. As shown in Table II, our method achieves significant better performance in minimizing recovery error than the state-of-the-art methods for our dataset. We consider the signal reconstruction error as a function of the number of filters (i.e., number of measurements) used, where the sensing matrix $\Phi$ is drawn from Gaussian distribution. As shown in Figure 2, our hybrid method consistently delivers superior reconstruction quality.

IV. CONCLUSION

We propose compressive spectrometers that can have lower manufacturing cost. This is because unlike conventional filter-based spectrometers, our method does not require filters with small leakage, and uses much fewer filters for signal reconstruction.

Our method leverages the fact that spectrum signals tend to exhibit a few spikes over a smooth curve. By enforcing sparsity (for spikes) and smoothness in the signal recovery process, we achieve low reconstruction error even under significant compression (Figure 2). We validate our method with real measurements from spectrometers, and release our dataset to the community to facilitate research.
This work is supported in part by gifts from the Intel Corporation and in part by the Naval Supply Systems Command award under the Naval Postgraduate School Agreements No. N00244-15-0050 and No. N00244-16-1-0018.

ACKNOWLEDGEMENTS

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